STUDIES IN THE AZOPYRIDINE SERIES

Submitted as a Thesis for the Degree of Ph.D. of Edinburgh University

by

ANDREW W. HENDERSON, B.Sc.

May, 1952.

INDEX

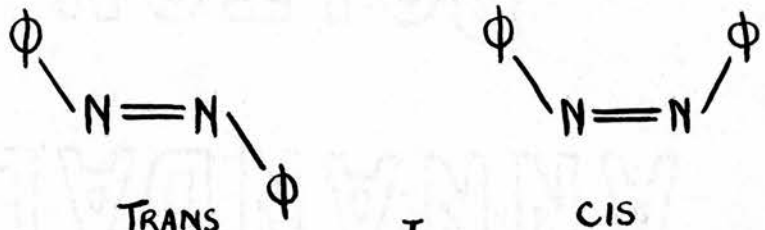
INTRODUCTION

Hartley (1) was the first to report a new form of azobenzene which was obtained when a solution of the normal material was exposed to light. This was not unexpected since when the directions of the orbitals of nitrogen are examined it is seen that two forms of azobenzene are indeed possible. Ammonia for much the same reason is found to have a pyramidal shape (2) with nitrogen at the apex. W.H. Mills (3), resolving compounds with the grouping $\geq C = N-R$ showed that when nitrogen is doubly bound, the third valency must lie out of the plane containing the double bond. Pauling (4) gives the carbon - nitrogen - nitrogen angle in methyl azide as 120^{o}.

Providing then that there is no steric, kinetic or resonance interference it is to be expected that wherever a nitrogen atom is linked by a double bond, there will be two geometrically distinct ways in which the residual valency will be directed. Substances with two nitrogen atoms linked by a double bond have been studied and isomers of diazotates, diazocyanides and azoxy compounds have been found, (5, 6). Further, irradiation with light is known to convert stable <u>trans</u> forms to geometrical isomers with the unstable <u>cis</u> configuration. Examples of this are furnished by fumaric and maleic acids (7), stilbene (8), oximes (9), and azoxybenzene (6).

The/

The common azobenzene is known to have a trans structure by virtue of its zero dipole moment (10). This was confirmed by Robertson (11) who proved by x-ray analysis that the molecule was planar and trans. Therefore it appeared that the new azobenzene was the missing cis isomer, the two being related as in (I).



I

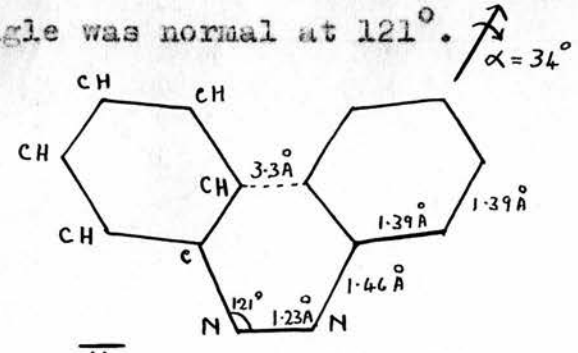
Hartley (12), comparing the properties of the two isomers, showed that while the M.P. of the new form was 71.4°C. compared to 68°C. for azobenzene, yet the eutectic between the two was 41°C. Melting gradually transformed cis into trans. 25% yields were obtained by irradiation of solutions of trans and separation was by fractional crystallisation. The heat of transition of cis to trans was about 12 kg. cals./g. mol. The new form was more soluble in polar solvents but was unstable to strong acids and reverted to trans under their influence. Light absorption in the blue region was greater for cis than for trans azobenzene, (XXV).

Taking advantage of their different adsorptive powers Zechmeister (13), and Cook (14), were able to separate the cis from the trans chromatographically. The latter's general observation taken for a number of aromatic/

aromatic azo compounds was that the more hydrophilic cis compounds were strongly adsorbed at the top of the columns while the trans compounds passed through easily (15). Some of the cis compounds were more and some less stable than azobenzene and some were not isolated at all; and while p-iodoazobenzene and m-nitroazobenzene appeared most stable of all, no rule for the existence or otherwise of cis isomers could be formulated. Characteristic differences in the absorption spectra of the two forms are found (16 and 17). Trans azo compounds show maximum absorption at ca. 3,200 - 3,700Å and 4,400 - 4,700Å. Little change in λ but conspicuous changes in ε_A at the longer wavelength are noted with the new cis materials.

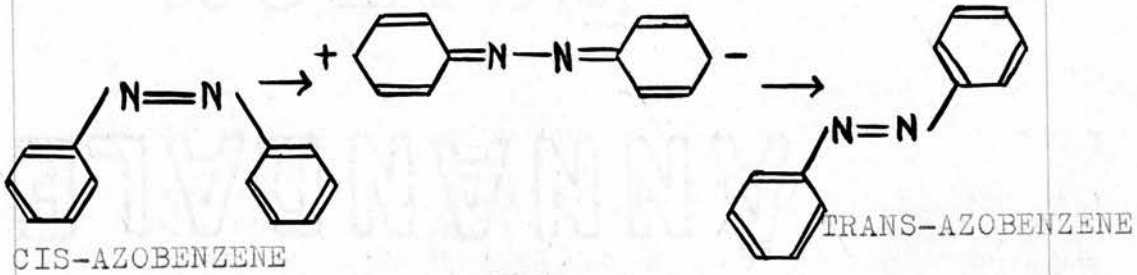
Le Fevre and Hartley (18), measured the dipole moment of cis-azobenzene and found it to be 3D. This compared favourably with the known dipoles of the azoxybenzenes 1·7 and 4·7 D, (19). Robertson (20 and 21) completed an x-ray analysis of the new isomer and showed that in the crystalline state the unstable form has indeed a cis configuration (II).

To allow for steric interference, each benzene ring was twisted out of alignment by about 34°. The -N=N-C angle was normal at 121°.



II

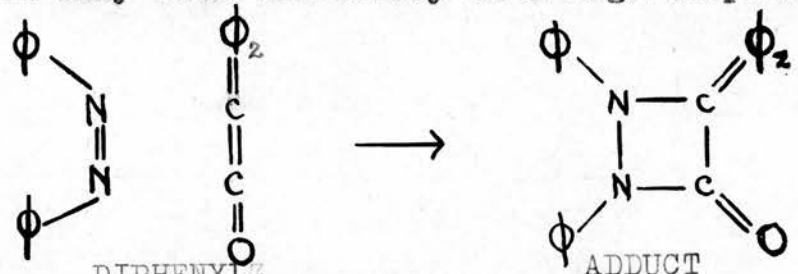
Significant was the =N-C< bond-length of 1.46Å which showed practically no double-bond character, the normal =N-C< distance being about 1·47Å. Single bond character here and double-bonding between the two nitrogens is necessary to prevent rotation of the group =N-ϕ and retrogression to the stable trans structure (III).



CIS-AZOBENZENE TRANS-AZOBENZENE

III

Cook (22) found that cis easily formed an adduct with diphenylketene but that the reaction with trans occurred only with difficulty at a high temperature (IV).



CIS-AZOBENZENE DIPHENYL-KETENE ADDUCT

IV

Other work - Calderbank and Le Fevre (23) on the dipole moments of benzocinnoline and its N -oxide; Van Auwers (24) with density and molecular refraction; Winkel and Siebert (25) polarography - seems to bear out the original conclusion.

The evidence presented above is strongly in favour of the geometrical isomerism of azo-compounds but Hodgson (26) does not accept this and states that "a double compound of azoxybenzene and hydrazobenzene exhibits/

exhibits far more convincingly many of the reactions of cis." His contentions shortly are:-

1. The ease of transformation of cis to trans = the ease of reaction of hydrazobenzene and azoxybenzene to give trans.
2. Molecular weight determinations show unexpected deviations.
3. The action of concentrated acid on cis resembles that with azoxybenzene.
4. The greater solubility in polar solvents is more reasonably accounted for by a molecular compound of azoxybenzene and hydrazobenzene.
5. Ultra-violet absorption spectra are displaced the "wrong" way.
6. The heat of combustion difference between cis and trans corresponds to that for hydrazobenzene+ azoxybenzene $\longrightarrow$ trans, 10·7 k/cals.
7. Analyses figures are doubted (similar papers are (27)).

Replies have been made by Le Fevre (28) and Waters (29).

It was at this stage considered that more light might be brought to bear on the supposed "compound" by application of Kofler's "contact methods" (30).

Secondly, in view of the little known of the azopyridine series it was considered to be of interest to investigate some of its simpler members. That azopyridine compounds are rare is largely due to the difficult diazotisation of the 2- and 4- aminopyridines (31)/

(31, 32 and 33), while 3-aminopyridine is not easily obtained in quantity. Diazonium compounds will couple at the 4 position in 2:6-disubstituted pyridines and the azopyridines resulting are used as bactericides (34). Otherwise alkaline reduction of nitropyridines or oxidation of aminopyridines are the methods known for the preparation of simple azo-derivatives, (35, 36, 37 and 38).

A claim, later found to be erroneous, of isomerism of 2:2'-azobis-pyridine had been made (35) and this was further investigated.

While research was in progress, Huang Hsinmin and Mann (39) reported two apparently stable isomeric azo-indoles. Also Le Fevre (40) reported some evidence for the existence of 2:2'-azobis-pyridine in cis formation. This was also then suspected and the isomer has now been isolated.

Faessinger and Brown (41) have produced some phenylazopyridines by a method similar but more complicated, to the one developed herein.

EXPERIMENTAL

Kofler's Methods

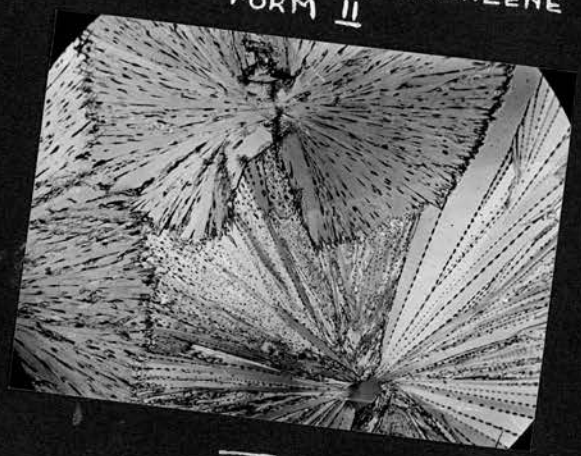
A polarising microscope fitted with an electric hot-stage, whose temperature is accurately recorded by a calibrated thermometer, is the apparatus upon which Kofler has based his analytical methods. Simple melting points are taken by placing a small quantity of material on a microscope slide and covering it with a cover - slip. The temperature is raised and the behaviour of the substance is observed with transmitted ordinary or polarised light. The material may sublime, change habit, give off a liquid of crystallisation, decompose or simply melt. The state of "equilibrium" when recrystallisation into the melt is taking place from solid "seeds" is quite characteristic of the substance (P. V and VI). If recrystallisation is slow, polymorphism is to be expected and quick cooling may cause the melt to solidify to an unstable modification: this is easily seen with the microscope (P. VII, VIII, IX).

The main advance due to Kofler is his "Contact - method" which will now be briefly described. With a simple melting - point a substance may not be sufficiently characterised, hence further identification is necessary; this is forthcoming on/

PHOTOMICROGRAPHS

V
EQILIBRIUM, AZOXYBENZENE
FORM II

VI
EQUILIBRIUM, AZOXYBENZENE
FORM I



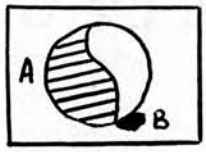
VII
O:O'-DICHLOROAZOXYBENZENE
FORMS II + I

VIII
AS VII AFTER TEN MINUTES
FORM III GROWING

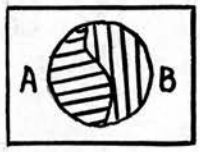
IX
COMPLETELY TRANSFORMED TO III

on the introduction of a reference substance whose eutectic temperature with the unknown material is noted. The reference substance may also be chosen to give a molecular compound with the unknown material and sometimes solid solutions occur. These two-component systems are examined as follows.

Let the unknown material be A and the reference material be B; A melts higher than B. A is melted on a slide so that it fills about half the space underneath the cover-slip and allowed to solidify (X). Next, a small quantity of B is placed on the

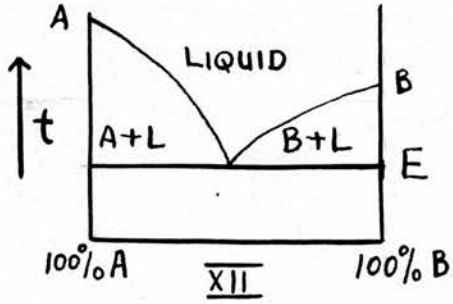


X

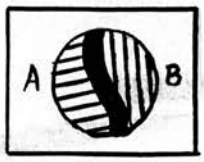


XI

slide and heated above its melting point so that it runs under the cover-slip,(XI). There is a "contact - zone" between A and B and in it every composition is present from 100%A to 100%B. When solidification has recurred the temperature is raised while observations are made on the contact area. When liquid is observed we have reached the eutectic temperature E and this is noted (XII,XIII).

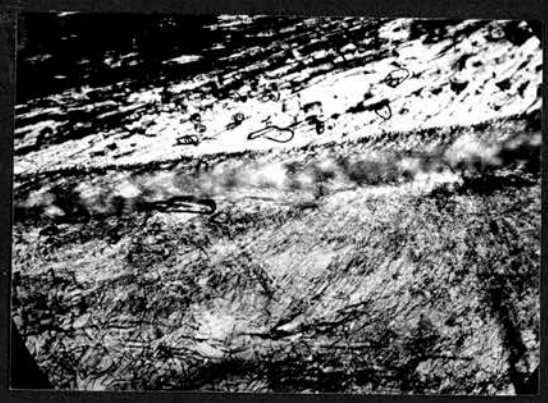


XII



XIII

Azobenzene/



XVI

CONTACT-PREP. OF PHENYLACETIC-ACID AND 2:2'-AZOBIS-PYRIDINE

XVII

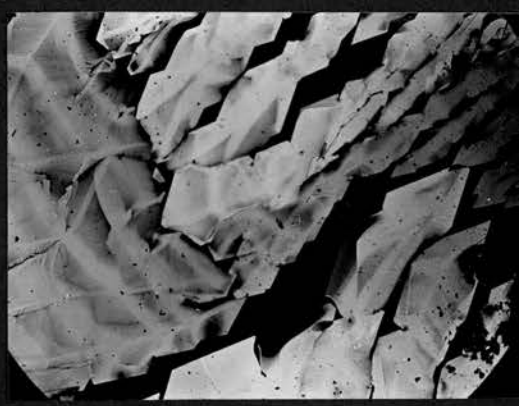
AS XVI AT 56°C

XVIII

AS XVI AT 63°C

XXI

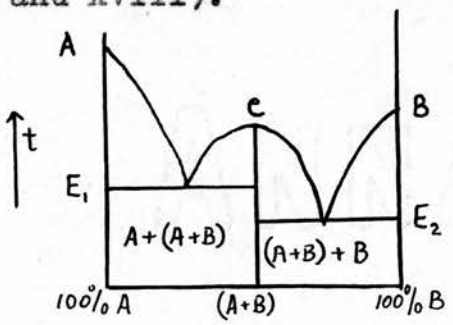
CIS-AZOBENZENE AFTER FOUR MELTS



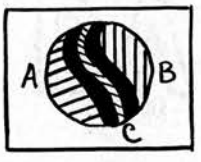
XXII

MAINLY TRANS-AZOBENZENE BY HEATING CIS

Azobenzene and benzil are the normal reference materials. If A is somewhat basic or is a hydrocarbon, picric-acid may be selected as B. Due to the formation of the molecular compound, two eutectic temperatures should then be observed in the contact-zone as well as the melting-point of the compound C (if the latter melts homogeneously). With a diagram such as (XIV) the appearance should be as at (XV) when the temperature is between E_1 and C (P. XVI, XVII and XVIII).



XIV



XV

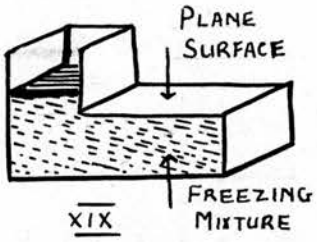
Under "crossed nicols", liquids being isotropic appear black hence quick observation of the important temperatures of two-component systems is obviously possible. These temperatures may be used for identification and characterisation and when solid-solutions are found, for elucidation of molecular structure by isomorphism.

The above procedure was used throughout the research.

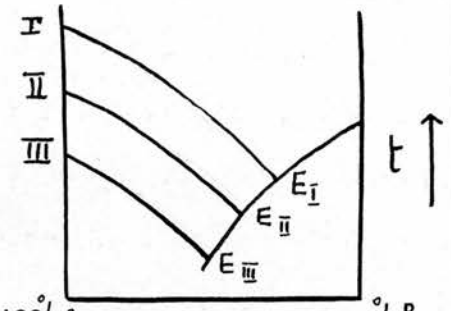
In addition however a supercooled liquid such as thymol as contact-agent (42) was used. When strong cooling methods were necessary the simple metal apparatus (XIX) shown (with side cut away) was useful.

In/

In other cases solid carbon dioxide was rubbed against the slide.



XIX



XX

When A is polymorphic several eutectics are to be expected with B and when reported they are listed against the form I, II or III in question, (XX). The reference substances are normally considered to be component B.

3:5-Dibromo-2-phenylazopyridine is taken as an example. It exists as a stable form I melting at 112°C after subliming to globules at 90°C. Quick cooling gives a monotropic form II melting at 96°C. The eutectic temperature of I with phenacetine is 97°C and of II it is 88°C. With benzil, I melts at 72°C and II at 66°C. A molecular compound with p-nitrophenol melts at 101°C when (XIV) E_1 is 88°C and E_2 86°C. Tabulation is as follows:-

Form	m.p.	Eutectic points with					
		Benzil	Phenacetine	p-Nitrophenol			
				E_1	C	E_2	
I	112	72	97	88	101	86	°C
II	96	66	88	83			°C

In descriptions of microscopic data it is emphasised that/

that polarised light has been used exclusively.
M.P. of Azobenzene 68°C, Benzil 95°C, p-nitrophenol 113°C.

Preparations and Melting Phenomena

AZOXY COMPOUNDS

Azoxybenzene

Commercial azoxybenzene was chromatographed on alumina with benzene as solvent and recrystallised three times from methanol. Yellow needles, m.p. 37·5°C. (lit. 36°C). Microscopy: melts without sublimation and solidifies with difficulty. Stable form I with high crystallisation velocity occurs in needles. Quick cooling of the melt gives monotropic type II in brilliant fans and spherulites m.p. 29·5°C, easily taken over by I

		Eutectic temperatures with				
Form	m.p.	Trans-Azobenzene	Benzil	Hydrazobenzene	cis-Azobenzene	
I	37·5	27	26	31·5	19-20	°C
II	29·5	Below 20	Below 20	19 5	Below 20	°C

All simple eutectics. (P.V and VI).

o-o'-Azoxytoluene

Made from o-nitrotoluene by the method of Zechmeister and Rom (42). The reaction gave a mixture that was purified on an alumina column with light petroleum (B.P. 60-80°C) as solvent. First fraction gave red solid, m.p. 55°C (lit. m.p. of o-o'-azotoluene, 55°C). Last fraction, yellow needles from methanol m.p. 59°C, (lit. 59°C).

$C_{14}H_{14}N_2O$ requires/

$C_{14}H_{14}N_2O$ requires C 74·2, H 6·2, N 12·4%

Found C 74·2, H 6·0, N 12·5%

Microscopy: melts sharply at 59°C. Equil. brilliant "laths".

		Eutectic temperatures with				
Form	m.p.	Azobenzene	Benzil	o-o'-Azotoluene	Azoxy-benzene	
I	59	37	43	Eutectic at 50°C Type III mixed crystals	23	°C

m-m'-Azoxytoluene

Made by Zechmeister's method from m-nitrotoluene. Purified on alumina with light petroleum, (B.P. 60-80°C) as solvent. Recrystallised three times from methanol, yellow needles, m.p. 34-5°C (lit. 38-9°C).
Microscopy: Equilibrium of form I bright needles. Cooling the melt with solid CO_2 gives bright spherulites, II which either melt about 5-10°C or are taken over by I; very similar to the monotropy of azoxybenzene.

		Eutectic temperatures with				
Form	m.p.	Azobenzene	Benzil	m-m'-Azotoluene	Azoxy-benzene	
I	34-5	Below 20	26	Type I mixed crystals	Below 20	°C

p:p'-Azoxytoluene

Made by Zechmeister's method from -nitrotoluene. Chromatographic separation on alumina with light petroleum (B.P. 60-80°C) as solvent gave the first fraction melting/

melting at 144 -145°C, red plates from the same solvent (lit. m.p. of p:p'-azotoluene 144°C). This then was p:p'-azotoluene. The last fraction, yellow needles from methanol melted 69-70°C (lit. m.p. of azoxytoluene 70°C).

$C_{14}H_{14}N_2O$ requires C 74·2, H 6·2, N 12·4%

found C 74·3, H 6·3, N 12·3%

Microscopy: Equilibrium shows liquid crystal formation II quickly followed by laths and rhombs of the stable form I. II is monotropic with respect to I and melts slightly below it, ca. 69·8°C. Contact temperatures have not been obtained with II owing to its instability.

		Eutectic temperatures with				
Form	m.p.	Azobenzene	Benzil	p-p'-Azotoluene	Azoxy-benzene	
I	69-70	37·5	50	Mixed crystals Type I	21	°C

o:o'-Dichloro-azoxybenzene

This substance resulted as a side - product from condensations of o-chloronitrosobenzene with amino-pyridines. From an alumina column of the reaction product the azoxycompound was obtained as first fraction; yellow neddles from methanol, m.p. 56-7°C (lit. 56°C).

Microscopy: quick cooling of the melt gives I, broad, brightly coloured laths m.p. 56°C and II, m.p. 51°C, close/

close-grained spherulites, monotropic with respect to I. III, very fine needles, m.p. 50°C takes over II quickly and I slowly. It is enantiotropic with respect to I and II with reversible points at 48°C and 45°C respectively (P. VII, VIII and IX).

		Eutectic Tempertatures with			
Form	m.p.	Azobenzene	Benzil	Phenacetine	
I	56-7	29	35-6	50	°C
II	51	Not obtained	Not Obtained	Not Obtained	°C
III	50	33	39-40	Not Obtained	°C

Azobenzene Homologues

o:o'-Azotoluene, m.p. 55°C (lit. 55°C) obtained during reduction o -nitrotoluene to form azoxytoluene.

p:p'-Azotoluene, m.p. 144-145°C (lit. 144°C) was obtained during reduction of p-nitrotoluene to form azoxytoluene. (Polymorphic).

Hydrazobenzene

(44). White flakes from light petroleum, (B.P. 60-80°C), m.p. 128°C (lit. 125°C).

Microscopy: Equil. dull plates and spherulites

	Eutectic temperatures with			
m.p.	Azobenzene	Azoxybenzene	cis-Azobenzene	
128	59	31·5	58	°C

There is no mixed crystal formation and the eutectic with azoxybenzene could not be seeded with cis/

cis or trans azobenzene between 25 and 60°C.

trans-p-Iodoazobenzene

Nitrosobenzene (5·2g) and p-iodoaniline (10·6g) in glacial acetic acid (80 ml) were shaken for 24 hrs. The crude product was filtered and recrystallised from ethanol. Yield 10g (66%) orange needles, m.p. 104-7°C (Lit. 105°C).
Microscopy: sublimes to needles from 70°C. Apparent transformation on heating. Cooling shows several polymorphic forms.

		Eutectic temperatures with	
Form	m.p.	cis-p-Iodoazobenzene	trans-m-Nitroazobenzene
I	104-7	62·5	72.5 °C

m-Nitroazobenzene

Nitrosobenzene (5·2g) and m-nitroaniline (6·7g) were dissolved in glacial acetic acid (80 ml) and shaken 24 hrs. (45). The yellow needles are filtered off and recrystallised from ethyl alcohol, m.p. 95-97°C (lit. 96°C). Yield 6g, (55%).
Microscopy: quick cooling shows extensive polymorphism.

		Eutectic temperatures with	
Form	m.p.	cis-m-Nitroazobenzene	trans-p-Iodoazobenzene
I	95-7	58	72·5 °C

Preparations of Azobis-pyridines

2:2'-Azobis-pyridine by method "A"

2:2'-Azobis-pyridine was made by Kirpal and Reiter (46) by oxidation of 2-aminopyridine with hypochlorite. In repeating the experiment the following quantities were used. 2-aminopyridine, commercial, recrystallised once from light petroleum, m.p. 57°C (lit. 57·5°C), (1g, 1 mol.) was dissolved in water (5 ml). KOH (8g, 14 mol) in 50 ml water when cool, was mixed into a slurry with finely-ground $Ca(OCl)_2$, (16g, 11 mol). With mechanical stirring the solution of the amine was dropped in, the temperature being kept below 15°C. After two hours stirring, the mixture was extracted with ether, (2 x 100 ml), followed by chloroform (2 x 250 ml).

The ether extract gave orange flakes (0·1g) from light petroleum, (B.P. 60-80°C), m.p. 80-81°C. The Chloroform extract gave deep red needles (0·5g) from light petroleum, m.p. 85°C (lit. 87°C).

Total yield 0·6g (61%).

This method is found to be generally applicable to amino-pyridines. Extraction of the reaction-mixture is normally with chloroform alone. A stable gel often appears on extracting but this may be broken by cautious addition of conc. HCl. Where the amine is not soluble in water it is finely ground and mixed to a paste with benzene and added in small quantities to the stirred hypochlorite.

Method "B"/

Method "B"

Where in method "A" there is danger of chlorination of the amine, the alternative of oxidation to the nitro-compound and alkaline reduction of this to the azo can be effective. No change was made on the method of Kirpal and Bohm (35), in which a mixture of hydrogen peroxide and sulphuric acid is used to oxidise the aminopyridine to the nitropyridine and this is then reduced with alkaline arsenious oxide to the azo derivative.

In a typical experiment 20g. 2 - aminopyridine gave 4g. 2:2' -azobis-pyridine m.p. 85-86°C. after recrystallisation from light petroleum (B.P. 60-80°C.) Overall yield, 20%.

2:2'-Azobis-pyridine

Method "A" gave two products m.p. 81°C. and 85°C. These were originally thought to be geometric isomers (35), but Kirpal (36) found that the lower-melting product contained 5-Chloro-2:2'-azobis-pyridine which had not been detected in the analyses. Method "B", of course, gives pure 2:2'-azobis-pyridine. The method then found for purification for the product from "A" was fractional crystallisation of the octohydrate from water. A preferable separation is by partition chromatography, there being no purification on alumina.

Silica gel was made according to the method of Martin and Synge (47) from commercial waterglass.

The/

The material after drying was sieved through a gauze of 40 gauge.

SiO_2 (30g) was mixed with water (16ml) and stirred till no lumps remained. The solvent was water-saturated ether and the material was suspended in this and a column made up in the usual way (ca. 2 x 30cm.). The product,(0.2g), from "A", melting at 81°C. was dissolved in the same medium and placed on the column. Development caused the impurity, 5-chloro-2:2'-azobis-pyridine, m.p. 136°C., to be quickly washed out, leaving the pure material at the top of the column. This was eluted with an ether-alcohol mixture (20:1) and crystallised from light petroleum (B.P. 60-80°C.), giving the familiar deep-red needles,(0.19g),m.p. 85-86°C., identical with those from experiment "B".

The addition of small quantities of the chloro compound to 2:2'-azobis-pyridine solutions in light petroleum caused the appearance of the flaky orange solid whose melting-point is generally between 78 and 82°C. This is identical with the ether extract from experiment "A".

Microscopy:2:2'-azobis-pyridine melts 85-86°C. (lit. 87°C.), sublimes to globules from 70°C. Equil., needles and laths, deep-red and orange.

	Eutectic temperatures with								
m.p.	Azobenzene	Benzil	p-Nitrophenol			Phenylacetic acid			cis-2:2'-Azobispyridine
			E_1	C	E_2	E_1	C	E_2	
85.6	51	60	69	151	103	55	74	60	56

°C

85.6 ?

Trans 3:3'-azobispyridine	Cis-3:3'-azobispyridine	5-Cl-2:2'-azobis pyridine
77	53	75. Type V mixed crystals.

°C

The impure 2:2'-azobis-pyridine from the ether extraction of "A", m.p. 81°C., leaflets from light petroleum.

Microscopy: cooling the melt gives spherulites, very rarely needles or laths.

	Eutectic temperatures with						
m.p.	Azobenzene	Benzil	Phenylacetic acid			5-Cl-2:2'-azobispyridine	2:2'-azobispyridine
			E_1	C	E_2		
81	48	57	52	71	57	75, Type V mixed crystals	apparently Type I M.C.

°C

5:5'-Dibromo-2:2'-azobis-pyridine

2-Aminopyridine was brominated by the method of Tschitschibabin (48). 2-Amino-5-bromopyridine crystallised from benzene in colourless plates, m.p. 137°C. (lit., 137°C.).

The bromoamine (10g) was oxidised by method "A".

The/

The chloroform extract was evaporated to dryness carefully, extracted with benzene and run through a short column to remove tar. Recrystallisation from benzene-light petroleum gave orange needles of 5:5'-dibromo-2:2'-azobis-pyridine, m.p. 260°C. (lit.,235°C.).

$C_{10}H_6N_4Br_2$ requires C 35.1; H 1.8; N 16.4; Br 46.7
found C 35.0; H 1.5; N 16.3; Br 47.3

The preparation of the compound had previously been reported by Bystritskaya and Kirsanov (37).

Microscopy: The crystals sublime at 150°C. to needles and rhombs. By 240°C. it is all sublimed and at 260°C. it melts and decomposes.

Eutectic with dicyandiamide, 174°C.

3:3'-5:5'-Tetrabromo-2:2'-azobis-pyridine

2-Amino-3:5-dibromopyridine was obtained by Tschitschibabin's method (48), as buff needles, m.p. 104-5°C.,(lit. 105°C.).

The compound (10g) was oxidised by method "A" and treated as before the monobromo compound. When the benzene solution of the azo compound from the alumina column was evaporated to small bulk the solid separated from it in tiny orange needles, m.p. 103°C., yield 2.3g,(23%).

$C_{10}H_4N_4Br_4$ requires C 24.0; H 0.8; N 11.2; Br 64.0.
found C 24.3; H 1.7; N 11.0; Br 63.0.

Microscopy: The crystals melt after subliming to diamonds/

diamonds and laths from 60°C. Equilibrium of form I, planks. Quick cooling gives fine spherulites, II, m.p. 88°C unstable with respect to I.

Form	m.p.	Eutectic temperatures with					
		Azobenzene	Benzil	p -Nitrophenol			
				E_1	C	E_2	
I	103	50	71	77	104	97	°C
II	88	50	62	70			°C

3:3'-Dinitro-2:2'-azobis-pyridine

2-Aminopyridine was nitrated by the method of Caldwell and Kornfeld (49). 2-Amino-3-nitropyridine separated in yellow needles from ethanol, m.p. 162°C (lit. 162°C)., 5g of which on oxidation by method "A" gave (from benzene) 1·1g (23%) of tiny red rhombs m.p. 230°C.

$C_{10}H_6N_6O_4$ requires C 43·8, H 2·2, N 30·7%
Found C 43·9, H 2·3, N 30·5%

In solution or when heated the compound has a nauseating odour. It is strongly adsorbed on alumina with a dark blue-green colour. In alkali it is deep red; in acid yellow.
Microscopy: The compound sublimes at 160°C to rhombs and melts with decomposition at 230°C.
Eutectic with dicyandiamide, 174°C.

5:5'-Dinitro-2:2'-azobis-pyridine/

5:5'-Dinitro-2:2'-azobis-pyridine

2-Amino-5-nitropyridine, yellow plates (from acetone), m.p. 186-188°C (lit. 188°C) was made as above by Caldwell and Kornfeld's method.

Oxidation of the compound (5g) by method "A" gave 2g (41%) of brownish-red very fine needles, m.p.220°C from benzene.

$C_{10}H_6N_6O_4$ requires C 43·8, H 2·2, N 30·7%
Found C 44·0, H 2·7, N 30·9%

The adsorption, odour and pH effect are similar to those of the previous compound.
Microscopy: Melts with decomposition at 220°C.
No sublimation. Eutectic with dicyandiamide 185°C.

4:4'-Dimethyl-2:2'-azobis-pyridine

Since there was the possibility of chlorination by method "A", "B" was employed.

2-Amino-4-methylpyridine, m.p. 98°C (lit. 98°C) (11g), was oxidised to 2-nitro-4-methylpyridine, white leaflets (light petroleum, B.P. 60-80°C). m.p. 65·5-66·5°C. Yield 5·1g (36%).

$C_6H_6N_2O_2$ requires C 52·2, H 4·4, N 20·3%
Found C 52·2, H 4·1, N 20·4%

This compound has since been reported by Wiley and Hartman (38) who give a m.p. of 61-62°C.

2-Nitro-4-methylpyridine (4g) was reduced with alkaline arsenious oxide and gave 3g of yellow needles which melted 100-136°C. The material was dissolved/

dissolved in benzene and chromatographed on an alumina column. The first fractions melted over a range. Late fractions yielded 2g (65%) orange needles, m.p. 149-151°C from light petroleum, (B.P. 80-100°C.).

other methods for prep. 2-Amino-4-methyl quinoline

$C_{12}H_{12}N_4$ requires C 67.9; H 5.7; N 26.4 %
found C 68.0; H 5.7; N 26.0 %

Microscopy: Equil., orange needles at 150°C. Decomposes. Sublimes from 110°C to planks and needles. Not polymorphic.

	Eutectic temperatures with					
m.p.	Azobenzene	Benzil	p-Nitrophenol			
			E_1	C	E_2	
149-151	61	82	104	157	97	°C

3:3'-Azobis-pyridine

3-Aminopyridine was made from nicotinamide by the method given in "Organic Syntheses" (50), m.p. 63-64°C. (lit. 63-64°C.). 3-Aminopyridine (5g) was oxidised by method "A" giving 3.1g of crude product, orange needles (from benzene), m.p. 138°C. (lit. 141°C.). This was dissolved in benzene and run through a short column of alumina. Yield 2.5g, (51%), fine orange needles from light petroleum (B.P. 100-120°C.), m.p. 140°C.

Method "B"/

Method "B"

3-Nitropyridine was made by the method of Friedl (51), as modified by Kirpal and Reiter (52). The yields were small, ca. 5% (53). Recrystallisation from water gave large needles, m.p. 41°C. (lit. 41°C).

3-Nitropyridine (5g) was treated with an alkaline solution of As_2O_3 for 45 mins. (37). Kirpal (35) obtains azoxypyridine in this way. However, after purification on an alumina colmmn in benzene and recryatallisation from light petroleum (B.P. 100-120°C.), 3g (62%), of the azo compound are obtained as orange needles, m.p. 138-140°C. (lit. 141°C.).

Microscopy: Sublimes from 70°C. in needles. Equil., needles and planks. Decomposes on melting and is not polymorphic.

	Eutectic temperatures with						
m.p.	Azobenzene	Benzil	3-Phenyl-azo-pyridine	p-Nitro-phenol			
				E_1	C	E_2	
138-40	62	84	Mixed, Cryst. (Type IQ with II	112	143	107	°C.

cis-3:3'-Azobis-pyridine	trans-2:2'-Azobis-pyridine	cis-2:2'-Azobis-pyridine	
72	77	68	°C.

4:4'-Azobis-pyridine

4-Aminopyridine was made by the method of Hertog and Overhoff (54). It was found essential to distil the commercial phthalic anhydride before use and even then poor yields resulted unless continuous extraction was used both for the removal of 4-nitropyridine-N-oxide and the 4-aminopyridine from the reaction mixtures.

A typical experiment gave 25% yield of 4-amino-pyridine (calculated on pyridine used), white flakes from toluene - light petroleum, m.p. 156-7°C (lit. 157-8°C).

4-Aminopyridine (2g) when oxidised by method "A" gave 1.1g of orange needles from light petroleum, (B.P. 60-80°C), m.p. 105-106°C. This was taken up in benzene and chromatographed on alumina. The main fraction recrystallised from light petroleum, (B.P. 60-80°C), in orange needles, 0.8g (41%), m.p. 108-9°C.

$C_{10}H_8N_4$ requires C 65.2, H 4.4, N 30.4%
Found C 64.6, H 4.7, N 30.2%

cf. den Hertog & Combé Rec., 1951, 70, 585

Microscopy: Sublimes to needles, rhombs, diamonds and globules from 90°C. Equilibrium, needles. Apparently not polymorphic.

	Eutectic temperatures with									
m.p.	Azobenzene	Benzil	p-Nitro-phenol			Hydro-quinone			4-Phenylazo-pyridine	
			E_1	C	E_2	E_1	C	E_2		
108-9	61	71	91	174	107	93	162	132	73	°C

Condensations/

Condensations between nitrosobenzenes and aminopyridines

A typical condensation of amine and nitroso-compound to give an azo-compound is found in "Organic Syntheses" (55) where glacial acetic acid is the condensing medium. (56 and 57).

Nitrosobenzene was made according to "Organic Syntheses" (58), m.p. 67°C (lit. 67°C).

Molecular quantities of 2-aminopyridine (1·9g) nitrosobenzene (2·1g), and glacial acetic acid (20 ml) were shaken at room temperature for 48 hours. There was no reaction. Similar quantities with glacial acetic acid (20 ml) and sulphuric acid (0·2 ml) even when shaken for 48 hours did not react.

The above mixtures when heated for varying periods of time up to 30 mins. gave only the starting materials.

Fusion of molecular quantities of amine and nitrosobenzene gave a violent reaction, but yielded no azo compound.

Condensation was ultimately achieved in the presence of concentrated alkali. Pyridine, aqueous sodium carbonate or water fail as condensing agents. This is called

Method "C" for phenylazopyridines

Phenyl-2-azopyridine is taken as an example.

2-Aminopyridine (5g) was added to a warm 50% solution (50 ml) of NaOH in water. This was gently heated and benzene (3 ml) added. Nitrosobenzene (6g) was/

was added in small portions over a period of 10 minutes while the flask was agitated and gently heated; heating was continued for a further 10 minutes. Extraction with benzene at about 30°C. (3 x 100ml) gave a deep red solution which was heated with charcoal (1g), filtered and concentrated under reduced pressure to 100ml. The solution was run on to an alumina column. When development with benzene was started, nitrosobenzene or its condensation product, azoxybenzene, was washed out first. The azo compound appeared next as an orange - red band. This was eluted with benzene, evaporated carefully to dryness and crystallised from light petroleum (B.P. 40-60°C) at a low temperature.

Yield 8g (82%) red needles m.p. 32-34°C.

Method "C" is applicable to halogeno and alkyl-aminopyridines. Nitroaminopyridines and 2:6-diaminopyridine under the above conditions failed to condense.

Purification in the experiments described has always been on columns of alumina (30g alumina to 1g material) with benzene as solvent. Owing to the relatively high vapour pressure of the azo compounds it might be possible to effect purification on a larger scale by high-vacuum distillation.

2-Phenylazopyridine

Prepared/

Prepared as described by method "C". Recrystallised from light petroleum (B.P. 40-60°C) at a low temperature giving red needles, m.p. 32-34°C.

$C_{11}H_9N_3$ requires C 72.1; H 4.9; N 22.9%

found C 72.1; H 4.7; N 22.4%

Microscopy: Melts 32-34°C and recrystallises slowly. No polymorphism observed. Notable type I mixed - crystal formation with 2:2'-azobis-pyridine when needles of the latter appear gradually to penetrate right through a contact - prep.

	Eutectic temperatures with						
m.p.	Azobenzene	Benzil	2:2'-Azobis-pyridine	p-Nitrophenol			
				E_1	C	E_2	
32-34	Below 20	Below 20	Type I mixed crystals	22	104	78	°C

2-Phenylazo-5-bromopyridine

2-Amino-5-bromopyridine (4g) with nitrosobenzene (4.5g) were treated according to method "C". Yield 5.1g (86% on the amine), scarlet diamonds m.p. 115°C, from light petroleum (B.P. 60-80°C).

$C_{11}H_8N_3Br$ requires N 16.0; Br 30.5%

found N 15.8; Br 30.3%

Microscopy: sublimes from 60°C to globules and needles. Melts sharply at 115°C. Equil.I, laths and needles, brightly coloured with oblique ends. Quick cooling of the melt gives III, pale orange, fine structured spherulites. Heating III gives II and/

and I. II advances as needles with spear - shaped ends and is brightly refracting and is taken over by I.

III melts at 94°C and II at 100°C. II and III are monotropic with respect to I.

		Eutectic temperatures with						
Form	m.p.	Azobenzene	Benzil	Phen-acetine	p-Nitrophenol			
					E_1	C	E_2	
I	115	Not obt.	72	99	86	95	81	°C
II	100	"	Not obtainable					°C
III	94	"	66	89				°C

2-Phenylazo-3:5-dibromopyridine

2-Amino-3:5-dibromopyridine (5g) and nitrosobenzene (5g) were treated according to method "C" giving 5.5g (84%) deep crimson tablets from light petroleum (B.P. 60-80°C), m.p. 112°C.

$C_{11}H_7N_3Br_2$ requires N 12.3; Br 46.9%

found N 12.4; Br 46.8%

Microscopy: Sublimes from 90°C to globules and melts at 112°C. Equil. I, bright planks and rhombs. Quick cooling of the melt gives pale orange, close grained, opaque spherulites, II m.p. 95°C, unstable with respect to I. II may also be had by recrystallisation at low temperature from light petroleum (B.P. 40-60°C).

		Eutectic temperatures with						
Form	m.p.	Azobenzene	Benzil	Phen-acetine	p-Nitrophenol			
					E_1	C	E_2	
I	112	54	72	97	88	101	86	°C
II	95	51	66	88	83			°C

2-Phenylazo-4-methylpyridine

2-Amino-4-methylpyridine (4g) with nitrosobenzene (4.5g) were treated according to the method "C" giving 5g (68%), red prisms m.p. 55°C from light petroleum (B.P. 40-60°C).

$C_{12}H_{11}N_3$ requires C 73.1; H 5.6; N 21.3%

found C 73.1; H 5.5; N 21.1%

Microscopy: Slight sublimation occurs to give globules from 50°C. Equilibrium I, bright planks with oblique ends. Quick cooling of the melt gives monotropic fans II and III.

II Bright spherulites of broad planks including gas bubbles and having flat ends, m.p. 38°C.

III Fine structured, fibrous spherulites growing as needles, m.p. 32°C.

		Eutectic temperatures with						
Form	m.p.	Azobenzene	Benzil	p-Nitro-phenol			4:4'-Dimethyl-2:2'-azobis-pyridine	
				E_1	C	E_2		
I	55	31	41	49	113	84	46 i.e. Simple eutectic with I	°C
II	38	Below 20	Below 20					°C
III	32	"	"					°C

2-o-Chlorophenylazopyridine

o-Chloronitrosobenzene was made as described by Lutz and Lytton (59), m.p. 55°C (lit. 56°C).

2-Aminopyridine (0.90 gm) and o-chloronitroso-benzene (1·4 gm) were condensed together by method "C" giving 1 g (48%), red needles (from light petroleum B.P. 40-60°C), m.p. 54-55°C. (The first fraction from the alumina column gave 0·2g of o-o'-dichloroazoxybenzene which is described under "Azoxy Compounds").

$C_{11}H_8N_3Cl$ requires N 19·3, Cl 16·3%
Found N 18·8, Cl 15·8%

Microscopy: m.p. 54-55°C, sometimes sublimes to globules from 40°C. Only one form is observed and the equilibrium shows highly refracting needles.

	Eutectic Temperatures with					
m.p.	Azobenzene	Benzil	p-Nitrophenol			
			E_1	C	E_2	
54-5	31	40	40	97	80	°C

The appearance of the contact-prep. after remelting the contact zone seems to indicate a second molecular compound with p-nitrophenol inhomogeneously melting at 90°C, with a higher proportion of the azo compound.

3-Phenylazopyridine

3-Aminopyridine (4g) and nitrosobenzene (4·5g) were condensed by method "C". This gave 4·7g (60%)

of/

of orange leaflets (from light petroleum, B.P. 40-60°C), m.p. 52-3°C.

$C_{11}H_9N_3$ requires C 72·1, H 4·9, N 22·9%
Found C 73·3, H 4·7, N 22·4%

Microscopy: Sometimes sublimes to diamonds before melting at 53°C. Equilibrium of form I, broad flat areas of doubly-refracting crystal.

II Monotropic form by quick cooling of the melt, needles and laths, m.p. 44°C easily taken over by I.

		Eutectic temperatures with								
Form	m.p.	Azobenzene	Benzil	3-3'-Azobis-pyridine	p-Nitrophenol					
					E_1	C_1	E_2	C_2	E_3	
I	53	45, Type III mixed crystals	37	47	41	103	93	99	97	°C
II	44	Not obtainable	Not obtainable	Type I mixed crystals						°C

3-o-Chlorophenylazopyridine

3-Aminopyridine (3·8g) and o-chloronitrosobenzene (6g) were condensed by method "C". Yield 4·1g (47%) deep red needles from light petroleum (B.P. 40-60°C), m.p. 60°C.

$C_{11}H_8N_3Cl$ requires N 19·3, Cl 16·3%
Found N 19·7, Cl 16·8%

Microscopy: Melts at 60° after subliming at 55°C to globules. Equilibrium of form I, planks and needles with flat ends. Quick cooling gives II, m.p. 53°C, spherulites, close-grained and opaque; and III, brightly/

brightly-refracting and also fine-structured. II and III have a similar rate of growth. III is unstable with respect to II and I and II with respect to I. The melting point of III could not be obtained.

Form	m.p.	Eutectic temperatures with Azobenzene	Benzil	p-Nitrophenol E_1	p-Nitrophenol C	p-Nitrophenol E_2	
I	60	Below 20°C	45	49	115	82	°C
II	53	Below 20°C	40				°C
III	N.O.	Below 20°C	Not obtainable				°C

4-Phenylazopyridine

4-Aminopyridine (0·45g) and nitrosobenzene (0·55g) were condensed by method "C". Yield 0·6g (69%) orange leaflets from light petroleum (B.P. 60-80°C), m.p. 98°C.

$C_{11}H_9N_3$ requires C 72·1, H 4·9, N 22·9%
Found C 71·6, H 5·0, N 23·1%

Microscopy: Recrystallises quickly from the melt and is not polymorphic. Equilibrium, bright plates.

m.p.	Eutectic temperatures with Azobenzene	Benzil	p-Nitrophenol E_1	p-Nitrophenol C	p-Nitrophenol E_2	4-4'-Azobis pyridine	
98	61	71	74	89	70	73	°C

E. Koenigs (60) has prepared this compound by condensation of phenylhydrazine and 4-chloropyridine and oxidation of the resulting 4-phenylhydrazo-pyridine with nitrous acid. m.p. 98-99°C.

Other methods of introducing the azo group

Diazotisations of 2-aminopyridine failed in conc. sulphuric acid or conc. hydrochloric acid media possibly because the temperature used was not lower than 0°C. Koenigs (33) has found diazotisation possible and Tschitschibabin (32) describes coupling products of pyridine.

The methods of de Milt and Van Zandt (61) were not tried with aminopyridines.

Preliminary experiments seem to indicate that diazotisation and coupling of the N-methylsulphate derivative of 2-aminopyridine may be possible.

4-Nitropyridine-N-oxide on treatment with lithium-aluminium-hydride by the method of Nystrom and Brown (62) gave a deep-red colouration suggestive of an azo compound but this was not studied further.

Surprisingly, 2 and 3-nitropyridines gave no colour with the above reagent but this might have been due to traces of moisture which would interfere.

The Preparation of Cis-Azo-Compounds

This was effected by irradiation of solutions

with/

with a mercury-vapour lamp. By clamping the flask containing the trans solution 18 ins. from the lamp and 8 ins. above it it was possible to take advantage of the slight heating effect to circulate the solution.

The solvents were dried and stored over sodium wire.

Work with cis-azo compounds must be conducted in weak artificial light or in darkness; and the temperatures of solutions of cis-compounds should be kept as low as possible. Though more stable in the crystalline state, they should not be exposed to daylight any more than necessary.

Cis-azobenzene

This was made according to Cook (14) by illumination of a solution of the trans isomer in benzene and separation on an alumina column. In a typical experiment, azobenzene (5g), in dry benzene (250 ml), was irradiated for 12 hrs. A sintered glass filter-funnel, 3 ins. x 3 ins., porosity 3, was used as a short column with alumina in benzene to a depth of 1½ ins. as adsorbent. The azobenzene solution was added in the usual way and developed under gentle suction till the strongly adsorbed cis layer was free from the trans: the latter was recovered. Elution with benzene containing acetone (20:1), gave a solution of the cis compound which was evaporated at a low pressure and temperature.

The/

The bright red solid recrystallised from light petroleum (B.P. 40-60°C) and appeared as diamonds and tablets, m.p. 71°C (lit. 71·4°C).

Microscopy: A sample sublimed to globules at about 55°C and melted at 71°C. Cooling gave broad, flat needles (P XXI) followed by smaller needles penetrating in all directions. This form melted at 40°C and was the eutectic mixture, while the broad needles remelted at 65°C and were decomposing cis-azobenzene. Heating and cooling caused the temperature of final melting to decrease and then to rise again while the eutectic mixture consistently melted at 40°C. Such a succession of temperatures was

71°C, 67, 64, 60, 58, 57, 54°C. The slide was then heated for five minutes at 70°C. Ensuing melting points were 51°C, 54, 61, 64, 65, 66, 66°C. The eutectic crystals did not appear on the slide at this stage (P XXII) and the material gave no further depression of m.p. with trans azobenzene whose m.p. was 68°C. To correlate observations on the slide in successive melts it was essential to cool it in the same way each time. The crystallisation velocity of both pure compounds appeared to be greater than that of the eutectic melt hence there is a tendency towards pseudo-eutectic syncrystallisation.

	Eutectic temperatures with		
m.p.	Azobenzene	Hydrazobenzene	Azoxybenzene
71	40	58	About 20 °C

Cis-m-Nitroazobenzene

This substance was prepared by irradation of the trans isomer in benzene followed by separation on alumina and recrystallisation from light petroleum (B.P. 40-60°C). Rhombs, m.p. 69-71°C (lit. 70°C), (15).

Microscopy: The temperature of disappearance of the last crystal descends from 71°C in successive melts to about 60°C, then rises to 94-95°C. (Trans melts at 96°C). Owing to the occurrence of trans-m-nitroazobenzene in polymorphic forms the intermediate temperatures are variable, but the material finally obtained gives no depression of melting-point with stable trans-m-nitroazobenzene.

	Eutectic temperatures with		
m.p.	Trans-Azobenzene	Trans-m-Nitroazobenzene	Cis-p-Iodoazobenzene
69-71	46	58	48·5 °C

Cis-p-Iodoazobenzene

The azo-compound was prepared from the trans isomer by irradiation in benzene and separated as before on alumina. Fine red leaflets from light petroleum (B.P. 40-60°C), m.p. 74-76°C (lit. 62°C), (15). The preparation was repeated and again the m.p. was 74-76°C.

Microscopy: Heating and cooling caused the melting-point to fall to 62·5°C and then to rise to 99°C.

At/

At this stage there was no further depression of melting-point with pure trans, (m.p. 104°C)

	Eutectic temperatures with	
m.p.	Trans-Azobenzene	Trans-p-Iodoazobenzene
74-76	48·5	63 °C

Trans-m-Nitroazobenzene	Cis-m-Nitroazobenzene
52	48·5 °C

Cis-p-Iodoazobenzene is very stable in the solid state and still melted at the same temperature after three months in the dark.

Cis-2:2'-Azobis-pyridine

(It was assumed at this stage that the stable isomers were trans, and the unstable, cis. Before any separation was attempted on an adsorbent, the starting material was passed in solution through a column of the same adsorbent to ensure that it was homogeneous.)

The trans isomer of 2:2'-azobis-pyridine (2g) in dry benzene (100 ml) was irradiated as before in a pyrex flask. Though the depth of the colour increased there was no separation on alumina. With the same adsorbent, different solvents were tried without/

without success.

Cis-azobenzene had been noted to be markedly more hydrophilic than trans (12). It was decided to take advantage of the differing distribution coefficients of cis and trans isomers between organic solvents and water and thereby effect separation. Accordingly a column, (30 x 2 cm), of silica gel was set up as already described for the purification of 2-2'-azobis-pyridine, except that water-saturated benzene was used as the solvent. A solution of trans 2:2'-azobis-pyridine (2g) in dry benzene (100 ml), was irradiated for 12 hrs., then shaken with water (1 ml), and the benzene layer run on the column. It was expected that the cis isomer would remain in the "aqueous" phase at the top of the column and that the less hydrophilic trans isomer would pass through in the benzene phase. When development with damp benzene was started a deep orange layer 6-8 cms.long remained at the top of the column while the pale orange solution which passed through was collected, evaporated and recrystallised from light petroleum (B.P. 40-60°C) giving deep-red needles m.p. 87°C. The mixed melting point with the hitherto known form was 56°C. Heating and cooling caused the fall and subsequent rise of the melting-point characteristic of a cis compound though in this case it appeared to be the less hydrophilic/

hydrophilic isomer. To achieve a complete separation the solvent was changed to benzene-light petroleum (B.P. 40-60°C), (1:1).

Trans-2:2'-Azobis-pyridine in dry benzene - light petroleum (50 ml) was irradiated for 12 hrs., shaken with water and the non-aqueous layer transferred to a silica column made up with the same solvent (30-40g. SiO_2 + 53% water in a column 2-5 cms width is suitable). Development with benzene - light petroleum washed down the cis band, (20 cm. long), leaving the trans as a dull orange layer (25 cm) in the column. The cis solution was evaporated at low temperature and recrystallised from light petroleum (B.P. 40-60°C). Yield 0·2 to 0·25g (10-12%), deep-red needles, m.p. 87°C.

(Cis), $C_{10}H_8N_4$ requires C 65·2, H 4·4, N 30·4%
Found C 65·6, H 4·3, N 30·1%

(The trans was recovered by elution with chloroform or benzene).

Microscopy: Sublimed to globules and needles from 60°C and melted at 87°C. Equilibrium variable. Solidified to deep-red fine-grained spherulites which grew out as needles. As the temperature fell this was followed by a feathery eutectic growth. Repeated heating and cooling gave the melting temperatures shown.

Disappearance of last crystal	77	80	78	68	67	55	57	°C
Start of melting	75	56	55	50	50	40	38	°C

Disappearance of last crystal	75	77	82	84	83	84	83	83	83	°C
Start of melting	35	35	35	35	60	55	55	55		°C

At this stage the eutectic residue had practically disappeared and there was no further decrease of melting temperature with a sample of pure trans.

The eutectic temperature of cis with trans is 56°C. The low value of 35°C in some observations can be explained on the assumption that there is a tendency towards polymorphism in either the cis or trans, or both. Another series of melts with seeding seemed to confirm this.

End of melting	87	77	80	78	68	67	55	°C
Start of melting		75	56	55	50	50	40	°C

The melt was seeded here with cis and melted again.

End of melting	70	75	80	°C
Start of melting	50	45	43	°C

It was next seeded with trans.

End of melting	85	85	°C
Start of melting	70	82	°C

This is seen to have a notable effect on the melting temperature.

	Eutectic temperatures with						
m.p.	Azobenzene	Benzil	p-Nitrophenol			Phenylacetic acid	
			E_1	C	E_2		
87	43	52	66	152	97	Below 20	°C

Trans-2:2'-Azobis-pyridine	Trans-3:3'-Azobis-pyridine	Cis-3:3'-Azobis-pyridine	
56	68	52	°C

Cis-2:2'-Azobis-pyridine is almost insoluble in water whereas the trans is extremely soluble and forms an octahydrate (36). It has been found that ferrous salts gave a deep blue colouration in aqueous solution with trans but not with the cis. (Spent columns of silica gel are always tinged blue owing to ferrous impurities in the water-glass. The blue colour is probably a "lake" and remains in the aqueous phase).

Trans-2:2'-Azobis-pyridine condenses in alcohol solution with copper sulphate to give a fluculent green precipitate and with silver nitrate to a white solid; those tests were not tried with the cis compound.

Cis-3:3'-Azobis-pyridine

A solution of trans-3:3'-azobis-pyridine in benzene - light petroleum (B.P. 60-80°C) was irradiated and run onto an alumina column. Development with/

with the same solvent gave no separation. Silica gel once more proved suitable.

Trans-3:3'-Azobis-pyridine (1g) in dry benzene-light petroleum (B.P. 40-60°C) (1:1), (50 ml), was irradiated for 12 hrs. Silica gel (30 g) with water (16 g) was made into a slurry with damp benzene-light petroleum and formed a column 30 x 2 cms. The irradiated solution was shaken with water (1 ml) and the non-aqueous layer transferred to the column. Development was with the same solvent, water - saturated, and left an orange band 16 cms long at the top of the column. The material that passed out was the trans isomer and melted at 139°C (lit. 142°C). Benzene-methanol (100:1) eluted the remaining band giving an orange solution. This was evaporated at low temperature and pressure and gave on recrystallisation from light petroleum (B.P. 40-60°C), scarlet rhombs m.p. 82°C.

$C_{10}H_8N_4$ requires C 65·2, H 4·4, N 30·4%
Found C 65·1, H 4·5, N 29·9%

Microscopy: Heating past the m.p. at 82°C causes small groups of laths to appear above 100°C. These grow as the temperature is raised until no liquid is left. In their turn they melt at 142°C. With pure trans-3:3'-azobis-pyridine this material gives no depression of melting-point. It appears that the new material is cis-3:3'-azobis-pyridine and that it is quickly transformed by melting to the more/

more stable trans isomer.

	Eutectic temperatures with		
m.p.	Azobenzene	Benzil	Trans-3:3'-Azobis-pyridine
82	53	57·5	72 °C

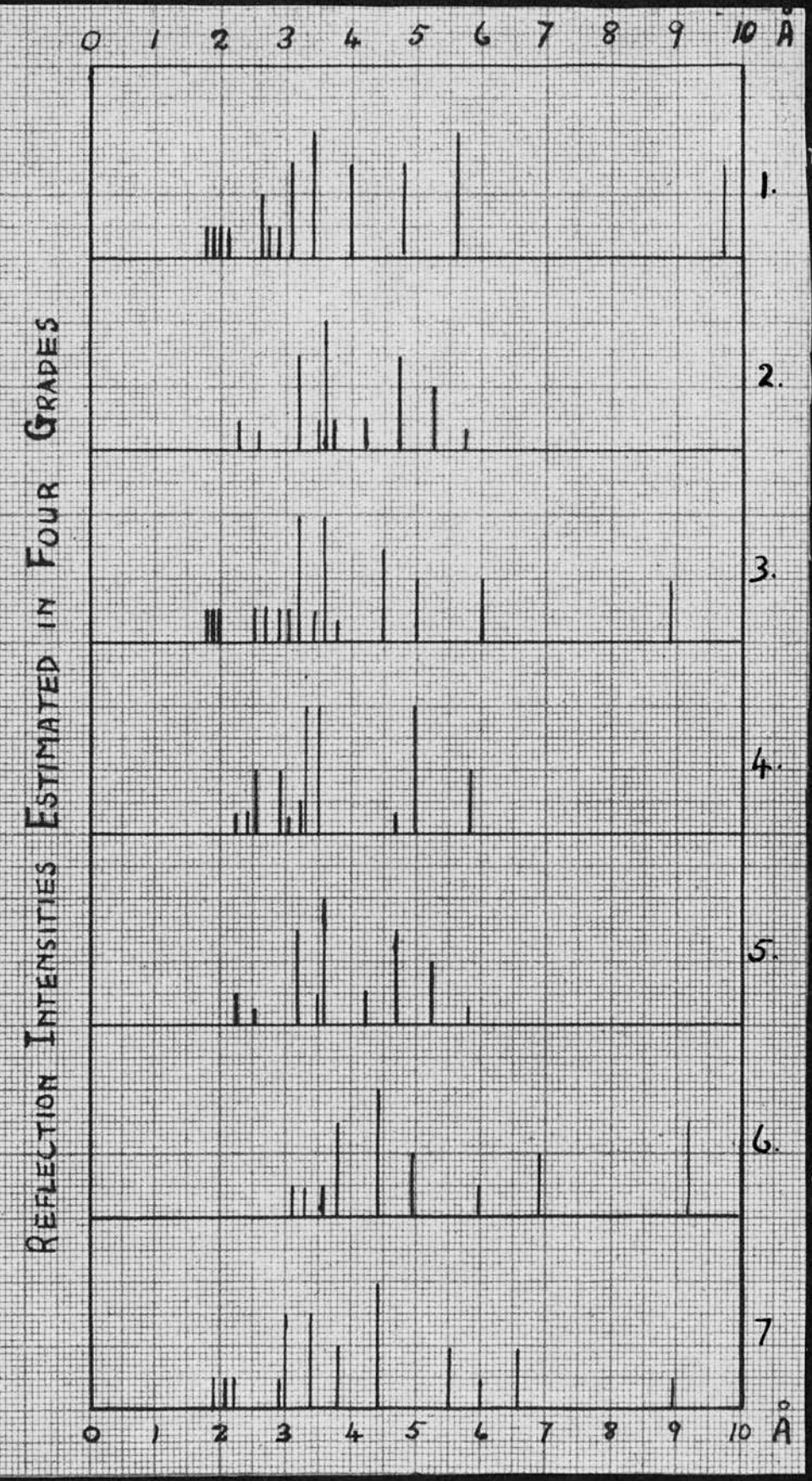
Trans-2:2'-Azobis-pyridine	Cis-2:2'-Azobis-pyridine
53	52 °C

Separationson alumina and silica gel have unsuccessfully been attempted with the following substances:-

4:4'-Azobis-pyridine, 3-phenylazopyridine, 2-o-chlorophenylazopyridine, 3-o-chlorophenylazopyridine, 4:4'-dimethyl-2:2'-azobis-pyridine, 5-bromo-2-phenylazopyridine.

X-ray powder photographs.

The x-ray powder camera used was a standard 9 cm. type. Later photographs were taken with a "Unicam" 9 cm. instrument. In the former camera the material was held in a celophane tube while in the latter it was contained in a fused silica tube. Ilford "Ilfex" film was used. Copper $k\alpha$ radiation with/



1. TRANS-2:2'-AZOBIS-PYRIDINE M.P. 86°C IDENTICAL WITH IMPURE SAMPLE M.P. 80-83°C

2. CIS-2:2'-AZOBIS-PYRIDINE

3. 5-CHLORO-2:2'-AZOBIS-PYRIDINE

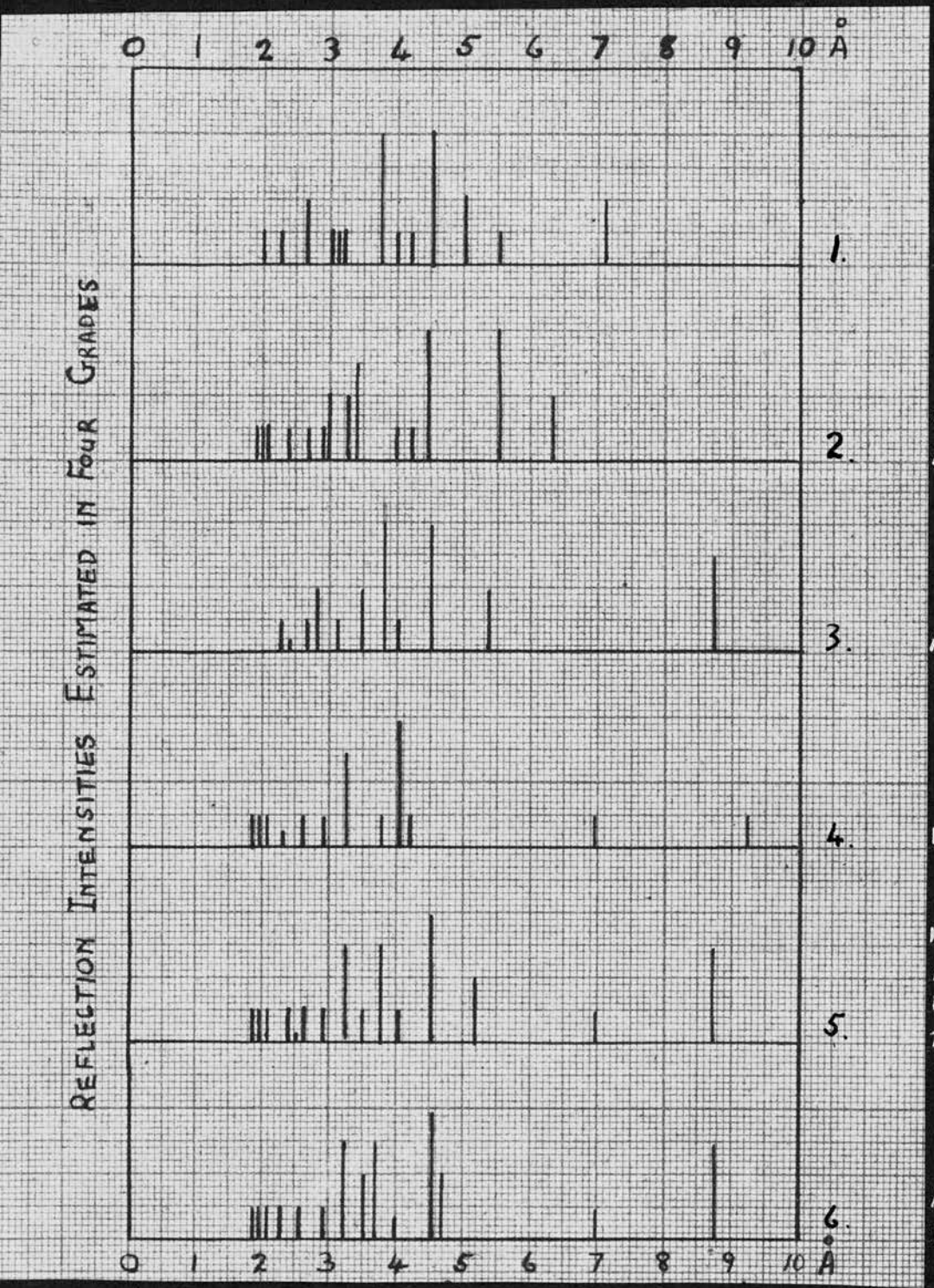
4. TRANS-3:3'-AZOBIS-PYRIDINE

5. CIS-3:3'-AZOBIS-PYRIDINE

6. α 1:2-1':2'-TETRAPHENYL-3:3'-AZOBISINDOLE

7. β 1:2-1':2'-TETRAPHENYL-3:3'-AZOBISINDOLE

XXIII


0 1 2 3 4 5 6 7 8 9 10 Å
REFLECTION INTENSITIES ESTIMATED IN FOUR GRADES
1.
TRANS-
AZOBENZENE
2.
CIS-
AZOBENZENE
3.
AZOXYBENZENE
4.
HYDRAZOBENZENE
5.
HYDRAZOBENZENE +
AZOXYBENZENE
RECRYSTALLISED
TOGETHER AT LOW TE
6.
AS ABOVE AT
ELEVATED TEMP.
0 1 2 3 4 5 6 7 8 9 10 Å
LATTICE SPACINGS

XXIV

with a nickel filter was employed, the wavelength thus being 1.54Å.

Using the classical Bragg equation it is possible to calculate the lattice spacings corresponding to the"reflections" on the film.(63). This was done and the intensity of the lines estimated visually.

The results are displayed by laying off d, the lattice spacing, horizontally, and drawing vertical lines at the appropriate distances of lengths proportionate to the reflection intensities, (XXIII and XXIV).

Especially in the azobenzene series it was noticed that there was a consistently strong reflection from planes with spacings about 4.5Å, as was also the case with the two azoindoles. Molecular models of cis and trans azobenzene were made from the data obtained by Robertson (64 and 21) and reciprocal lattice diagrams were drawn out to scale.

The spacing of ca. 4.5Å in trans azobenzene appears to be due to reflections from the planes (111), (201), ($\bar{1}$12), (20$\bar{3}$), and in cis-azobenzene from the plane (121).

Inspection of the models showed that the nitrogen atoms were contained in these planes. (There were of course other planes in which they also appeared).

Cooling/

Cooling Curves

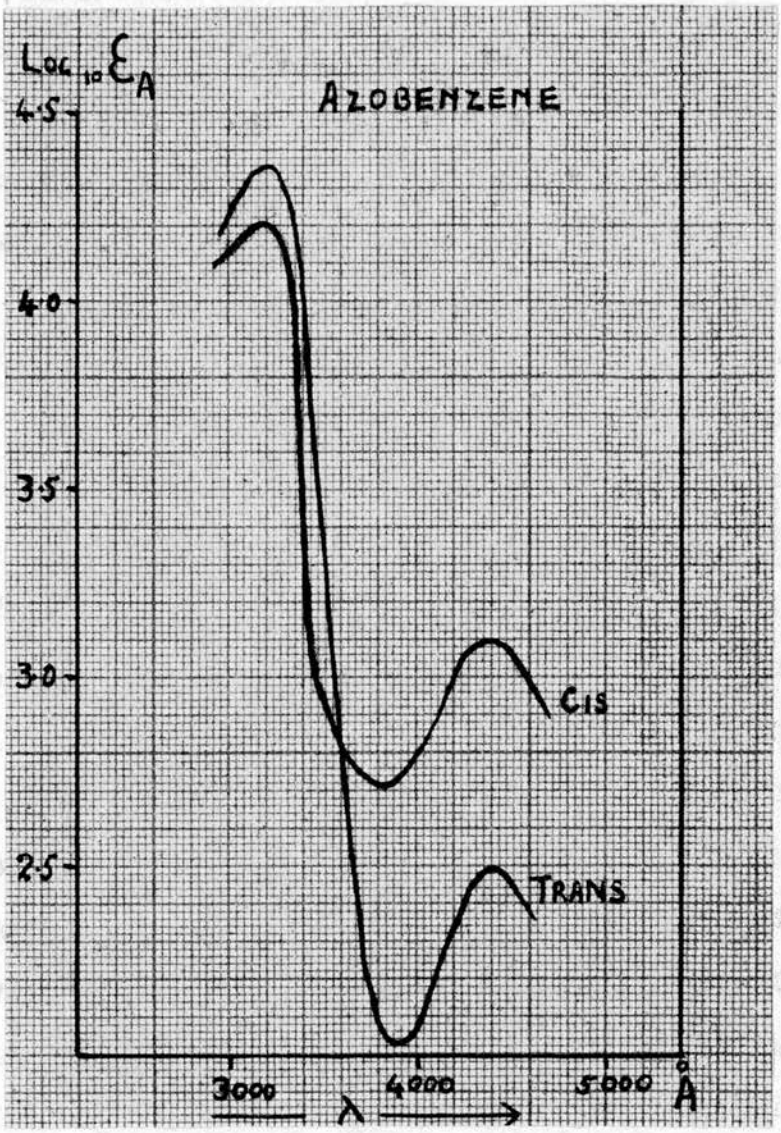
Normal molecular compounds, e.g. picrates, can be formed merely by melting together the two components. It might be expected that the molecular "compound" between hydrazobenzene and azoxybenzene, which Hodgson (26) contends is cis-azobenzene, would be present in an equimolecular melt of these two substances.

A simple apparatus was set up to determine the cooling curve of this system consisting of a small heat-insulated glass container with a copper - Constantan couple to determine the temperature of the contents. A sensitive galvanometer was calibrated with ice and boiling ether as alternative opposite junctions so that the temperature of the material in the tube could be estimated to 0.1°C (65).

In the system phenol:urea there is a molecular compound with the composition phenol:urea = 2:1 (66). The presence of this compound was evident by examination of cooling-curves obtained with the apparatus described, when mixtures of phenol and urea were melted together. Similar experiments with hydrazobenzene and azoxybenzene showed the existence of a simple mechanical mixture of the two and no trace of a molecular compound.

Light Absorption

Hartley/


Log 10 ε A
AZOBENZENE
4·5
4·0
3·5
3·0
2·5
CIS
TRANS
3000
λ
4000
5000
Å

Hartley (12) noted that cis azo compounds absorbed more strongly than trans at a wavelength of about 4500Å. An increase in the value log $\frac{I_o}{I}$ was noticed on irradiation of solutions of 2:2'-azobis-pyridine and with 3:3'-azobis-pyridine, but 4-phenylazopyridine and 4:4'-azobis-pyridine appeared to give either no change or a slight decrease. Since the changes were sometimes very slight and within the limits of experimental error, further work in absorptiometry was discontinued. The instrument used was a Hilger Photoelectric Absorptiometer , and filters "Ilford" No. 403 blue-green.

Absorption Spectra

The apparatus used was a Hilger "Spekker" ultra-violet spectroscope.

The results are displayed in tabular form (Table I) and graphically (XXV, XXVI, XXVII).

$\log_{10} \varepsilon_A = \log_{10} \left(\frac{\log \frac{I_o}{I}}{M} \right)$ was plotted against λ the wavelength in A^o.

Where

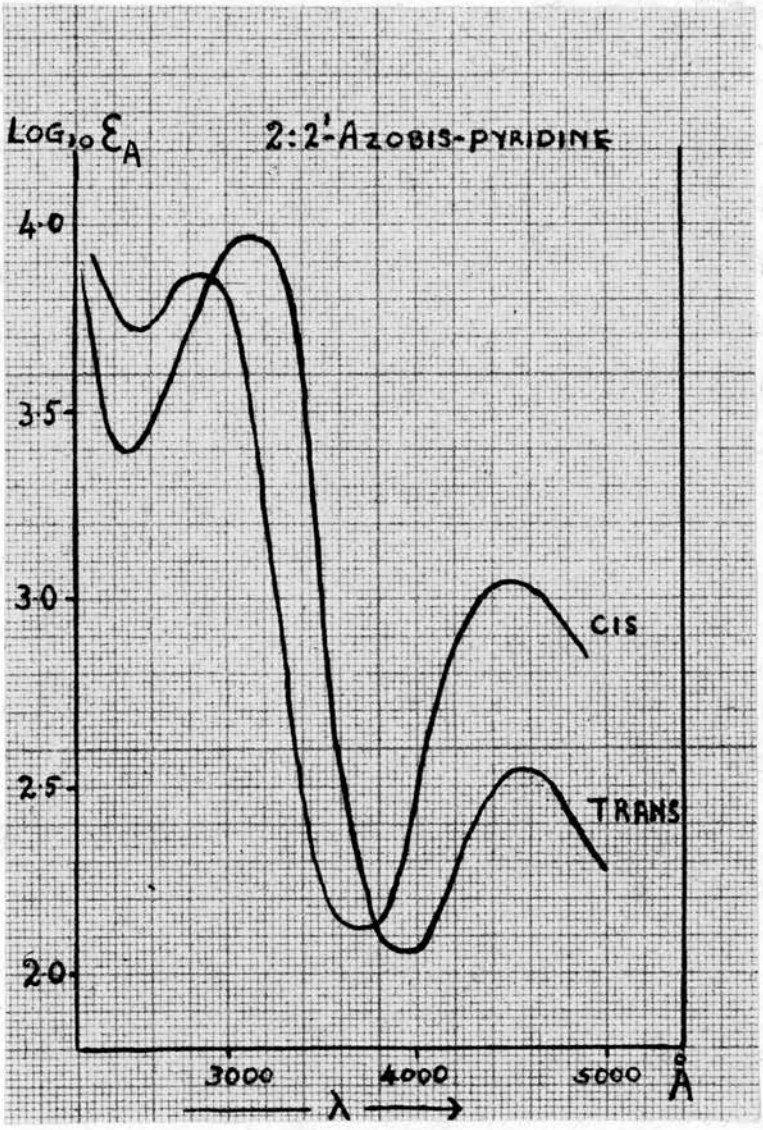
ε_A = Molecular absorption coefficient.

M = Molecular concentration in gm. mols./litre. c/

I_o is intensity of incident light.

I is transmitted light.

Determination/

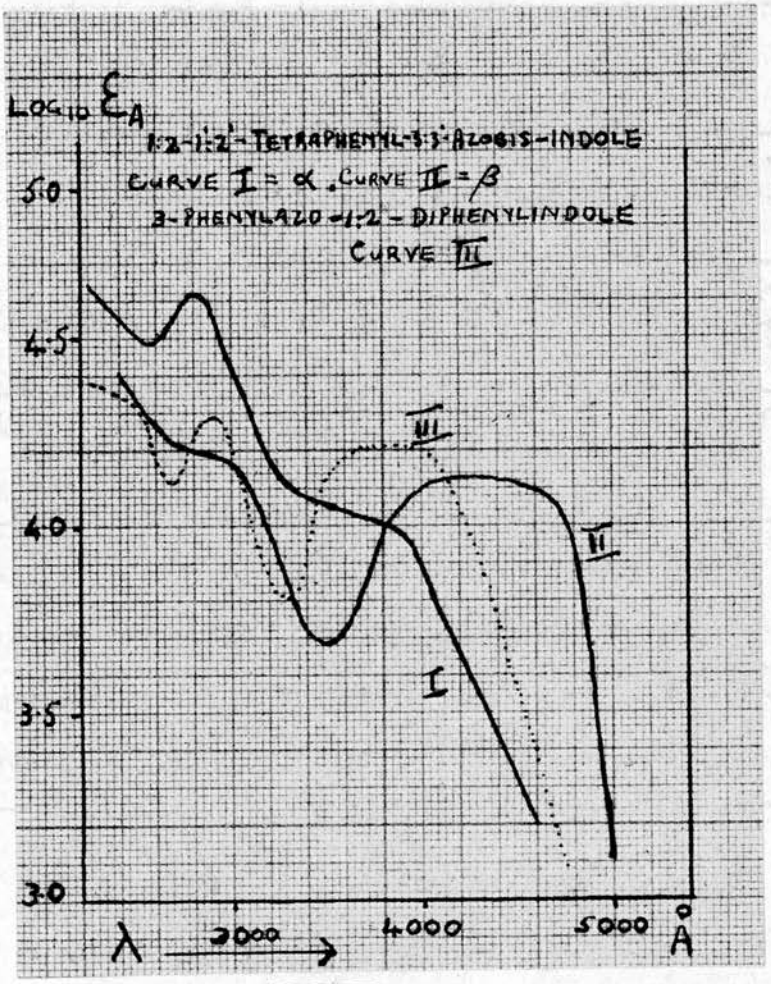

LOG10 εA
2:2'-AZOBIS-PYRIDINE
4·0
3·5
3·0
2·5
2·0
CIS
TRANS
3000
4000
5000
Å
λ

XXVI

TABLE I

U.V. Absorption Spectra

Substance	Solvent	λ Å	$\varepsilon_A >$ (Log 10)	$\varepsilon_A <$ (Log 10)	λ Å	$\varepsilon_A >$ (Log 10)	$\varepsilon_A <$ (Log 10)
Cis-2:2'-Azobis-pyridine	Ethanol	2820 2860	3·862	3·885	4370 4560	3·011	3·043
"	n-Hexane	2720 2880	3·934	3·953			
Trans-2:2'-Azobis-pyridine	Ethanol	3100 3180	3·959	3·983	4400 4650	2·499	2·578
1:2-Diphenyl-3:3'-azobis-indole (α)	Ethanol	2770 2820	4·599	4·614	Inflexion 3600	4·0	
"	Chloroform	Inflexion 2·850 3·060	4·498		Inflexion 3500 4000	4·071	
" (β)	Chloroform	Inflexion 2900	4·16		4000 4430	4·090	4·101
1:2-Diphenyl-indole-3-azobenzene	Chloroform	2860 2920	4·278	4·295	3700 3970	4·198	4·220


Log10 εA
2:2-1:2'-TETRAPHENYL-3:3'-AZOBIS-INDOLE
CURVE I = α . CURVE II = β
3-PHENYLAZO-1:2-DIPHENYLINDOLE
CURVE III
5·0
4·5
4·0
3·5
3·0
III
II
I
λ
3000
4000
5000
Å

XXVII

Determination of Dipole Moments

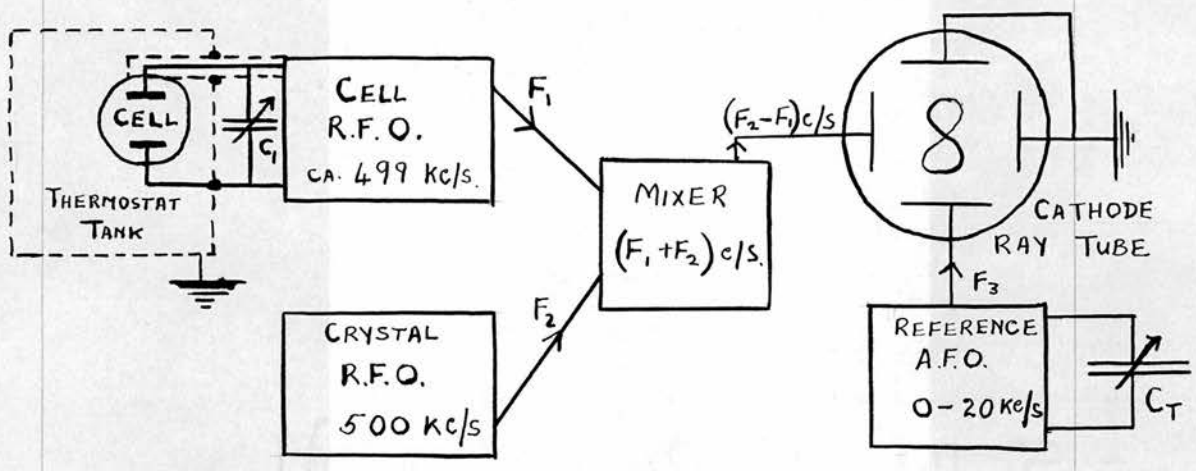
Le Fevre in "Dipole Moments" (67), has described the apparatus and methods in normal use for the determination of dielectric constants of solutions from which the dipole moment of the solute may be calculated. When, as is usual, a resonance method is employed measurement of the small difference in dielectric constant between solvent and dilute solution entails the measurement of small frequency changes. For this, a heterodyne circuit is simplest (68), and small frequency changes are measured indirectly with a Sullivan Standard variable condenser or its equivalent. The latter is a delicate and expensive component and in the circuit described below it was dispensed with apparently without great loss of accuracy or reliability.

In principle, the method involves the calibration of a variable condensor directly in terms of dielectric constant (69), and by using improved measuring circuits and introducing constant temperature conditions in the room ($21 \pm 0.3^{\circ}C$), it has been possible to determine the dielectric constant of liquids to the fourth decimal place. The accuracy of this procedure depends partly on temperature control and (70) elasticity of components but principally on the reliability and reproduceability of the calibration curve.

Measurement/

Measurement of Dielectric Constant

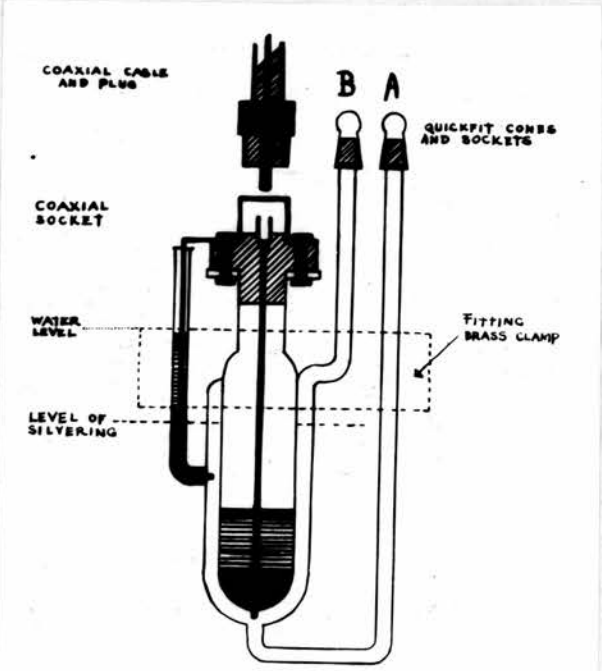
Schematically the apparatus was as shown (XXVIII). Ordinary good quality radio components were used throughout and the construction and wiring were as rigid as possible to give stability. The cell was held in a thermostat at 25 ± 0·1°C and the whole apparatus was in a room thermostated at 21 ± 0·3°C.



XXVIII

Frequency F_2 is invariable at 500 K.C/S. With benzene in the cell, F_1 is adjusted to give a vertical "figure eight" Lissajou figure on the C.R.T. when the A.F.O. tuning control is set at a predetermined position. This means that $(F_2 - F_1) = 2F_3$ and since F_3 at this point was arranged to be about 750 C./c., $F_1 \simeq 498{,}500$ C./s. Since the cell is in the tank circuit of the latter oscillator, when the benzene is changed for a solution whose dielectric constant will normally be greater than that of benzene, F_1 will decrease, $(F_2 - F_1)$ increase and hence to retain the same balance ratio, F_3 must rise also. F_3 is therefore varied in step with F_1 and to give a checking

frequency/


COAXIAL CABLE AND PLUG
B
A
QUICKFIT CONES AND SOCKETS
COAXIAL SOCKET
WATER LEVEL
FITTING BRASS CLAMP
LEVEL OF SILVERING

CELL

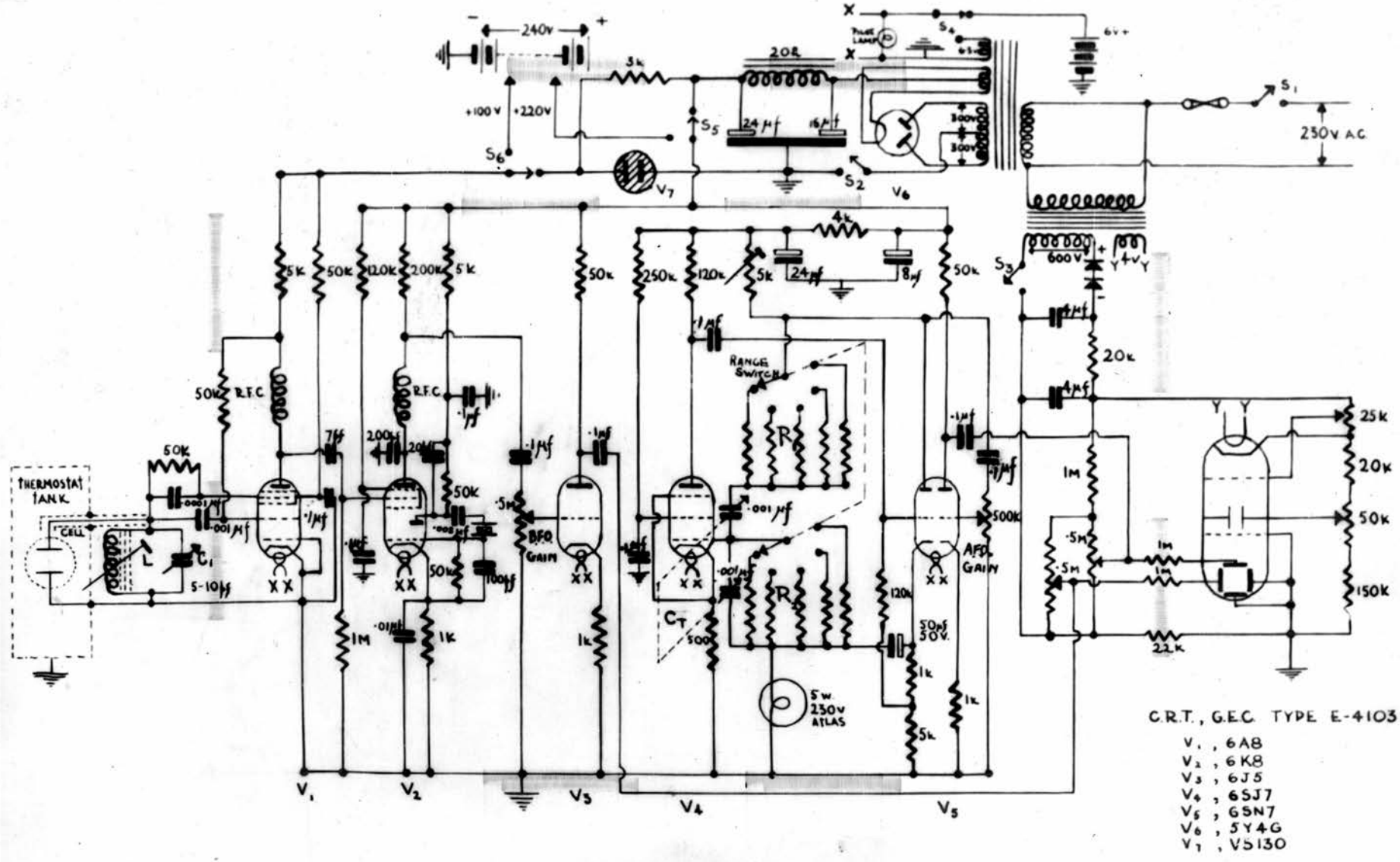
XXIX

frequency F_3 must be generated in a very steady oscillator. The A.F.O. tuning, C_T is calibrated in terms of dielectric constant of the liquid in the cell and estimations of capacity are not made. Since capacity is not measured, C_T can be an ordinary variable condensor in contrast to the Sullivan condensor in the more normal instrument.

Cell Diagram

The cell (XXIX) is as described by Le Fevre (67, p.36) except that a coaxial coupling is attached to a flange at the top by bolts cushioned with rubber washers. A plug of polythene ensures rigidity of the connections and the whole cell is held in the thermostat tank by a brass clamp. A coaxial cable connects the cell to the R.F.O. tank cct. (XXX). The cell R.F.O. contains a 6A8 heptode arranged to oscillate as a "transitron", (105) a type which is capable of high stability. The inductance L in the tank cct. is a variable dust-iron cored Eddystone coil of about 1·6 mh., while the capacitance apart from a very small trimming condensor C_1 is contributed by the cell and coaxial leads. Further stability is ensured by running the valve at a lower power (H.T. 100V.). This oscillator is completely screened from the rest of the assembly.

The output is fed through a small condensor to the/



C.R.T., G.E.C. TYPE E-4103-B-4

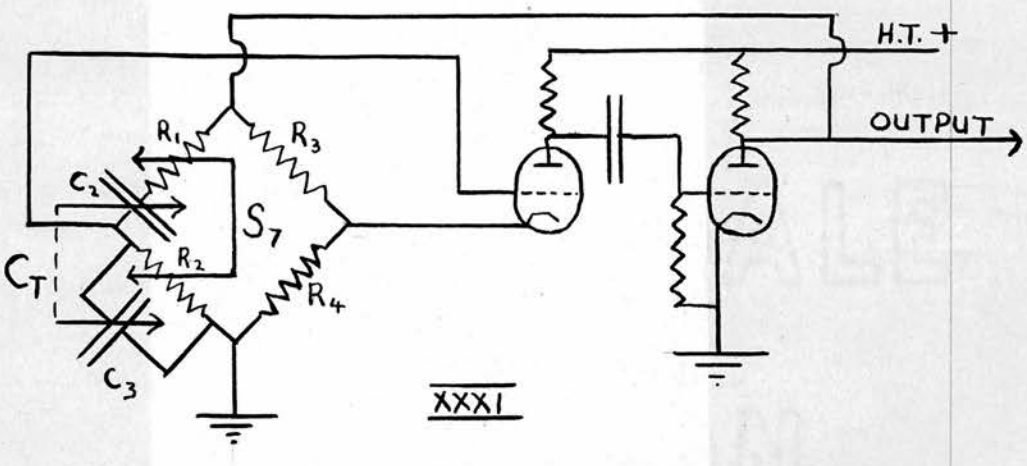
V1 , 6A8
V2 , 6K8
V3 , 6J5
V4 , 6SJ7
V5 , 6SN7
V6 , 5Y4G
V7 , V5130

DIELECTRIC CONSTANT METER

the grid of the "mixer" a 6K8 triode-hexode. A Pierce type oscillator is arranged in the triode part of this valve with control by a "G.E.C." quartz crystal (Type "HA", with low temperature coefficient) of 500 K C/S resonant frequency.

The audio beat frequency ($F_2 - F_1$) goes to a 6J5 acting as an R-C amplifier and from thence to the X plates of the C.R.T.

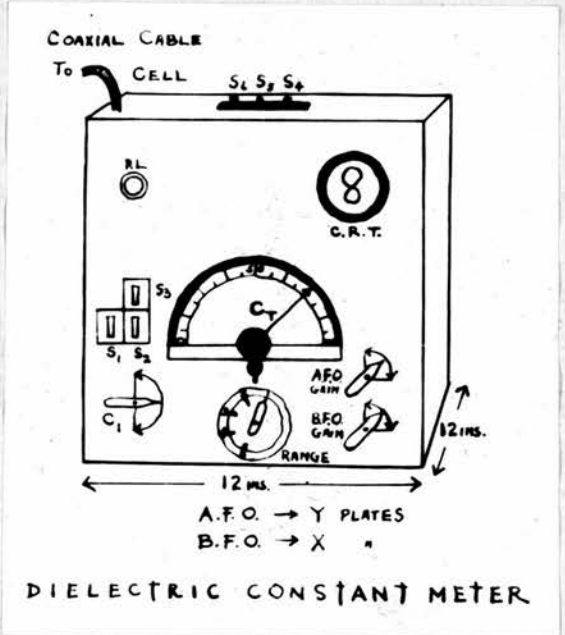
The audio frequency oscillator is similar to one described by Clifford (71) and is of the Wien bridge type shown schematically here (XXXI).



XXXI

Frequency is given by $\frac{1}{2\pi\sqrt{R_1R_2C_2C_3}}$. C_2 and C_3 are each of ·001 uf and ganged. Table II shows R_1 and R_2 values used and the approximate frequencies at the centre of the condensor scale. Coarse variations are made by switching the pairs of resistances with S_7, while fine adjustments of frequency are made by altering capacity with the tuning control C_T which is read off a dial of 100 divisions to ·01 division

Table II/



DIELECTRIC CONSTANT METER

Table II

Range	R_1 Ω	R_2 Ω	C_1 and C_2 at centre setting (C_T)	$F_3 = \frac{1}{2\pi\sqrt{C_2C_3R_1R_2}}$ c/s.
1	6M	4M	50·00	64
2	1.5M	1M	"	260
3	0.5M	330K	"	770
4	150K	90K	"	2,740
5	70K	50K	"	6,050

The valves employed in the A.F.O. are a 6SJ7 pentode and one half of a 6SN7 double triode. The output is amplified through the second half of the 6SN7 and applied to the Y plates of the C.R.T.

The cathode ray tube used was a G.E.C. Type E - 4103 - B - 4 whose screen is 3·5cm. in diameter and is quite big enough for the display required. It is arranged in a conventional circuit but metal rectifiers are used for the H.T. supply.

The instrument was designed originally for mains operation but local voltages varied from 170 - 240 V. causing wide changes of oscillator frequencies. Batteries were then substituted, 3 large - capacity accumulators supplying the L.T. and two 120 V. batteries in series the H.T. power. Extra switches S_4, (L.T.), S_5, (+100 V) and S_6 (+220 V) were installed to permit easy change from mains to battery working. When batteries were used the rectifier/

rectifier 5 Y 4 and the neon stabiliser S130 were removed. The C.R.T. was always mains operated. The brilliancy and focus controls along with X shift and Y shift resistances were placed inside the main casing while the X and Y amplitude controls were brought out to the front as shown (XXXII).

Switching on with battery working

A rigid method of switching on and off was essential to obtain reproduceability. The heater current was supplied to the valves by throwing S_4 and 4 minutes 45 seconds later the C.R.T. heater was switched on at S_1. At 5 minutes, S_5 and S_6 apply H.T. to the valves and oscillations start and at 5 minutes 15 seconds S_3 gives H.T. to the C.R.T. At 5 minutes 30 seconds the reading is made. Table III gives the same information.

Table III

Time, mins.	Switch	Effect
0·00	S_4	L.T. to Valves
4·75	S_1	L.T. to C.R.T.
5·00	S_5 and 6	H.T. to valves
5·25	S_3	H.T. to C.R.T.
5·50	Take reading	

Switching off is in the reverse order but no delays need be observed.

(This/

(This switching procedure is not necessarily the best but gave reproduceable results: whatever method is used should be adhered to exactly.)

At least 15 minutes interval is allowed between each reading so that the whole instrument may return to its original condition of temperature and humidity before the next reading is taken.

Filling the Cell

Benzene is normally blown from its container with dry air directly into the cell at A. Care is taken that no air is trapped in the capillaries and that they are filled up to the ground sockets. When solutions are examined they are poured quickly into the cell from the graduated flasks in which they were prepared and the ground caps immediately replaced on A and B (XXIX).

Emptying the Cell

A ground glass socket through which is supplied dry air is fitted to B while another connected with a suction pump is fitted to A. When the pump is started dry air is sucked through the cell behind the expelled liquid. Dry benzene is used for cleaning, and drying with a flow of dry air for a minute or two is adequate.

Setting up the instrument and mode of operation

In preliminary testing it was found that the sensitivity/

sensitivity on resistance ranges 1 and 2 was too great and hence the zero point was taken as C_T = 50·00 on range 3, an A.F. reference frequency of about 750 c/s. Pure dry benzene was put in the cell and after 10-15 minutes for the temperature to settle the variable core of L was adjusted till a vertical figure 8 was obtained on the screen. (N.B. care must be taken that F_1 is lower than F_2 when the figure appears). Further readings were taken at wide time intervals making minor adjustments with C_1 and occassionally changing the benzene. Further alteration of L was not required.

For a normal zero-setting, benzene is put in the cell and after 15 minutes with C_T at 50·00 on range 3, C_1 is adjusted to give the figure 8. Recalibration with benzene and C_1 is made about every two hours if the instrument is in constant use, otherwise before a solution of unknown dielectric constant is examined. This point 50·00 on range 3 is taken to correspond to a liquid of dielectric constant 2·2725 in the cell.

Calibration

Dilute solutions of nitrobenzene in benzene were taken as liquids of known dielectric constant. For dilute solutions, ε_{12}, the dielectric constant of a solution, varies linearly with f_1, the molar fraction of the solute (72 and 73). Data on nitrobenzene/

nitrobenzene solutions by Le Fevre (74, 75) and Jenkins (76) were collected and a graph of ε_{12} against f, extended to $f = 0$ at $\varepsilon = 2{\cdot}2725$. This graph was a straight line and ε could be found from it directly or by the relationship $\varepsilon_{12} = \frac{f_1 + 0{\cdot}99547}{{\cdot}043806}$

Nitrobenzene solutions were made up to cover the range of ε necessary. The main precaution required is to prevent access of water to the components which must therefore be exposed to the atmosphere for as short a time as possible. The weakest solutions were made up by dilution and comparisons with those made up directly showed that no significant error arose from this method. Since it was at the lower end of the scale near $\varepsilon = 2{\cdot}2725$ that most of the readings were required, thorough calibration was carried out here and only one or two points at ε greater than 2·35 taken. The upper limit of operation was about $\varepsilon = 3{\cdot}0$. Shortly before each calibration reading was made, the instrument was set via C_1 to the arbitrary zero with benzene of the same batch as that used for the solution.

The points ε_{12} against dial reading C_T fell on smooth curves for each resistance scale, (R_3, R_4, R_5), and this calibration (XXXIII) with different batches of nitrobenzene and benzene remained the same over a period of three months. (Since $\frac{\partial \varepsilon}{\partial C_T}$ becomes greater when/

when C_T is small the calibration was not taken below scale reading 15·00 on any scale). A graph of ε against C_T was drawn on a scale great enough to read ε to four places.

Accuracy

There is a slight drift in the zero-reading from time to time hence the absolute accuracy of measurement of ε is probably not better than $\pm$ 0·0002, but the difference $\varepsilon_{12} - \varepsilon_2$ (where ε_2 refers to the solvent) is possibly correct to the fourth place. No calibration of the oscillators or cell has been carried out separately. The accuracy of estimation of ε therefore depends on literature values of ε for benzene and nitrobenzene, the justifiable assumption that ε_{12} varies linearly with f_1 at low concentrations, and the purity of calibrating materials.

Purification of solvent and solutes

Benzene was treated as described by Le Fevre (67) and also Ubbelohde (77). Its refractive index was taken as the standard of purity. Found 1·49805. (Timmermans 1·49794, 1·49807, etc.).

Nitrobenzene was prepared according to Le Fevre (74) and Jenkins (76). Again refractive index proved a convenient method of checking purity. Found/

Found 1·55008, (Timmermans 1·55006).

Solid compounds were purified by chromatography followed by several crystallisations from pure dry solvents.

Advantages

1. Since F_1 can be set very close to F_2, extremely small changes of dielectric constant cause significant changes of $(F_2 - F_1)$ and this frequency, no matter how low, can be detected by comparison with F_3. Very weak solutions can be used.
2. The visual method of frequency comparison permits no error.
3. Since C_T is calibrated directly in terms of ε calculation is reduced to a minimum and $\varepsilon_{12}-\varepsilon_2$ is determined directly.
4. Any small differences in separate batches of benzene are immediately neutralised with C_1.
5. If a standard condensor became available it would be a simple matter to adapt the instrument to its use.
6. Benzene only has so far been used as solvent but calibration could be effected with any of the normally used materials.

Disadvantages/

Disadvantages

1. The calibration must be very carefully carried out and depends ultimately on the literature values for the calibrating materials.
2. Care must be taken not to disturb the cell or other components after calibration.
3. Though the switching of this instrument is somewhat complicated it could be simplified in designing a successor to work from batteries alone.
4. There is some drift of zero but this can be taken up with C_1.
5. Constant temperature conditions are necessary for successful operation.
6. The cell or circuit constants may change but this has not so far occurred and can always be checked with one or two solutions of known dielectric constant.
7. The solutions used were rather more dilute than normal hence errors will have more influence on the results.

The Calculation of Dipole Moments

The method of calculation is that adopted by Le Fevre and Vine (78). From this work,

$$_{\infty}P_1 = P_2(1-\beta) + C\alpha\varepsilon_2 \qquad (1)$$

where $_{\infty}P_1$ = total specific polarisation of the solute/

solute at infinite dilution.

p_2 = total polarisation of the solvent

$$= \frac{\varepsilon_2 - 1}{\varepsilon_2 + 2} \cdot \frac{1}{d_2}$$

$$C = \frac{3}{(\varepsilon_2 + 2)^2 d_2} ,$$

and ε refers to the dielectric constant, d to density, and suffixes 1, 2, and 12 refer to solute, solvent and solution respectively.

α is defined by $\varepsilon_{12} = \varepsilon_2(1 + \alpha W_1)$.

and β is defined by $d_{12} = d_2(1 + \beta W_1)$.

where W_1 is the weight-fraction of solute.

Atomic polarisation is neglected, (78) and electronic polarisation is taken to be represented by the molecular refraction for sodium light, $[R_L]_D$.

With M_1 = Molecular wt. of the solute, $_\infty P_1$ the total polarisation of the solute at infinite dilution = $M_1 . {}_\infty P_1$,

μ, the apparent dipole moment

$$= 0{\cdot}01273 \sqrt{(_\infty P_1 - [R_L]_D).T} \times 10^{-18} \text{ e.s.u.}$$

i.e. $$= 0{\cdot}01273 \sqrt{{}_o P_1 . T} \times 10^{-18} \text{ e.s.u.} \quad (2)$$

where $_o P_1 = (_\infty P_1 - [R_L]_D)$ the orientation polarisation at infinite dilution. Le Fevre later (73) indicates that when $\alpha\varepsilon_2$ shows dependence on concentration he extrapolates it to $W_1 = 0$. Since the solutions examined were very dilute this has not been done in

the/

the present work.

Other simplifications have been suggested for calculations by Guggenheim (79). He also (80) has shown that a good value of ${}_oP_1$ is given by

$$\frac{3M_1}{(\epsilon_2 + 2)^2 d_2} \cdot \left(\frac{\Delta}{W_1}\right)_{w_1 \to o} \qquad (3)$$

where $\left(\frac{\Delta}{W_1}\right)_{w_1 \to o}$ is defined by $\left(\frac{\epsilon_{12} + \epsilon_2}{W_1}\right)_{w_1 \to o} - \left(\frac{n_{12}^2 - n_2^2}{W_1}\right)_{w_1 \to o}$

Where n denotes refractive index.
From this μ is derived as before.

Some results have been worked out by both methods and give good agreement.

To check the possible occurrence of cis isomers when some single solutions of azo compounds were irradiated with ultra-violet light, ϵ_{12} was found before and after irradiation. No densities or refractive indices were known yet fair estimates of the apparent dipole moments of the solutes were arrived at by assuming a constant value for β throughout. This value, 0·26 was the average of all those observed for cis and trans, 2:2'- and 3:3'-azobispyridine and since all the compounds were of a similar nature, the error introduced would not be great and the apparent change in μ would be of the correct order. Molecular refractions were calculated. (Table V).

Refractive Indices/

Refractive Indices

A Pulfrich refractometer was used at 25°C but as a divided cell was not available the value of molecular refractivity was not very consistent especially at low concentrations. The values were, however, sufficiently accurate for the purpose. It is calculated from the formula

$$[R_L]_D = M_1 \left(r_2 + \frac{r_{12} - r_2}{w_1} \right)$$

(67 p.40)and (81) where r is specific refraction and suffixes have their usual meaning.

Alternatively values for molecular refraction may be estimated using the following values of "atomic" refractivities.

Br = 8·9cc. C = 2·4cc. H = 1·1cc.

C_6H_6 = 26·1cc. (67 p.39).

C_5H_5N = 24·1cc. (40 and 82).

Auwers (24) finds the molecular refractivity of cis-azobenzene as 59-60 cc and of trans as 63-64 cc. From this it would appear that the cis azo group contributes 9cc and the trans about 13 cc: but in this work the azo group was normally taken as contributing 9cc.

Densities at 25°C were measured with a pycnometer similar to one described by Lipkin, Davison, Harvey and Kurtz (83), with an accuracy of ± ·00002. The instrument was calibrated with water and a check with benzene/

benzene gave d = 0·87373.

(Timmermans, 0·87368, 0·87370, 0·87376 etc.)

Results (Table IV) are presented similarly to those of Le Fevre.

EXAMPLES

Trans-2:2'-Azobis-pyridine

w_1	$\varepsilon_{25^\circ}^{500}$	$d_4^{25^\circ}$	$\propto\varepsilon_2$	β	$n_D^{25^\circ}$	r_{12}	$[R_L]_D$	M_1
·00614	2·2864	·87540	2·26	·311	1·49889	·33531	56cc	184·2
·00674	2·2876	·87550	2·24	·300	1·49897	·33537	58cc	"

Then Average $\propto\varepsilon_2 = 2·25 \pm ·03$, average $\beta = ·305 \pm ·005$

$$_\infty p_1 = p_2 (1 - \beta) + C \propto \varepsilon_2 \qquad (1)$$

When $\varepsilon_2 = 2·2725$ and $d_2 = 0·87373$,

$p_2 = 0.34080$ and $C = 0.18810$ for the benzene used.

$\therefore$ Substituting the above values in (1) we have

$$_\infty p_1 = 0·660 \pm ·006$$

$$\therefore \quad _\infty P_1 = 0·660 \times 184·2 = 122 \pm 2 \text{ cc.}$$

$$[R_L]_D = 57 \pm 1 \text{ cc.}$$

$$\therefore \quad _o P_1 = 122 - 57 \text{ cc.} = 65 \pm 3 \text{ cc.}$$

$$\text{Also } \mu = ·01273 \sqrt{_o P_1 \times T} \times 10^{-18} \text{ e.s.u.} \qquad (2)$$

When $T = 25^\circ C$

$$\mu = ·01273 \sqrt{65 \times 298} \times 10^{-18} \text{ e.s.u.}$$

$$= 1·77 \pm 04 \times 10^{-18} \text{ e.s.u.}$$

Guggenheim's/

Guggenheim's Method. (without extrapolation of W_1 to zero).

The values for trans-2:2'-azobis-pyridine are again used.

$$\frac{3}{(\varepsilon_2 + 2)^2 d_2} = 0{\cdot}1881, \quad \text{from } (3)$$

and $$\frac{\Delta}{W_1} = \frac{2{\cdot}2864 - 2{\cdot}2725 - \{(1{\cdot}49805)^2 - (1{\cdot}49889)^2\}}{{\cdot}00614}$$

$$= 1{\cdot}838^{89}$$

$$\therefore \quad {}_oP_1 = 0{\cdot}1881 \times 1{\cdot}838^{89} \times 184{\cdot}2 \text{ cc.}$$

$$\doteq 64^{55} \text{ cc.}$$

Whence as before $\mu = 1{\cdot}76 \times 10^{-18}$ e.s.u.

When only $\frac{\varepsilon_{12} - \varepsilon_2}{W_1} = \propto\varepsilon_2$ is known,

p_1 is calculated from (1) assuming that $p_2(1 - \beta)$ is always 0·25.

Then ${}_\infty p_1 = 0{\cdot}25 + 0{\cdot}188 \propto \varepsilon_2$

$\therefore \quad {}_\infty P_2 = M(0{\cdot}25 + 0{\cdot}188 \propto \varepsilon_2)$ cc.

The calculated value of $[R_L]_D$ is then sub-tracted from ${}_\infty P_1$ to give ${}_oP_1$. μ is then calculated in the usual manner.

TABLE IV

	W_1	$\varepsilon_{25°}^{500}$	$d_{4°}^{25°}$	$\alpha\varepsilon_2$	β	n_D^{25}	τ_{12}	$[R_L]_D$ c.c.	Av. $\alpha\varepsilon_2$	Av. β
	0	2·2725	·87373			1·49805	·33550	26·2		
	Cis-2:2'-Azobis-pyridine									
	·00192	2·2910	·87413	9·6	·24	1·49860	·33567	64		
	·00178	2·2905	·87410	10·1	·24	1·49843	·33557	69	9·89	·24
(+)	·00452	2·3162	·87485	10·0	·28	1·49858	·33522	51	±·25	±·05
	·00427	2·3145	·87443	9·8	·19	1·49858	·33554	51		
	Trans-2:2'-Azobis-pyridine									
(+)	·00614	2·2864	·87540	2·26	·311	1·49889	·33531	56	2·25	·305
	·00674	2·2876	·87550	2·24	·300	1·49897	·33537	58	±·03	±·005
	Cis-3:3'-Azobis-pyridine									
	·00461	2·2940	·87489	4·66	·288	1·49858	·33538	57		
(+)	·00948	2·3202	·87618	5·03	·296	1·49904	·33512	54	5·05	·28
	·00281	2·2879	·87435	5·47	·252	1·49848	·33552	63	±·4	±·03
	Trans-3:3'-Azobis-pyridine									
	·00303	2·2844	·87431	3·92	·219	1·49874	·33565	71	4·01	·221
(+)	·00307	2·2851	·87433	4·10	·223	1·49862	·33559	67	±·09	±·002

Av. $[R_L]_D$ c.c.	M	$_\infty P_1$	$[R_L]_D^{CALC.}$	$[R_L]_D$ OBS.	$_0P_C$	$_0P_O$	μ_C	μ_O	μ_G
Cis-2:2'-Azobis-pyridine									
61±10	184·2	388±8	55±1	61±10	333±9	327±18	4·01±·05 D	4·0±·1 D	4·0 D
Trans-2:2'-Azobis-pyridine									
57±1	184·2	122±2	59±1	57±1	63±3	65±3	1·75±·04 D	1·77±·04 D	1·76 D
Cis-3:3'-Azobis-pyridine									
58 ±5	184·2	222±11	55±1	58±5	167±12	164±16	2·8 ±·1 D	2·85±·1 D	2·8 D
Trans-3:3'-Azobis-pyridine									
69±2	184·2	188±3	59±1	69±2	129±4	119±5	2·50±·04 D	2·40±·05 D	2·46 D

Suffix C ≡ calculated ; Suffix O ≡ observed ; G ≡ Guggenheim's method

The results marked (+) have been worked out by Guggenheim's method.

TABLE V

Substance	Irrad.	W_1	ε_{12}	$\alpha\varepsilon_2$	$c\alpha\varepsilon_2$	∞P_1	M	$_\infty P_1$	$[R_L]_D$	$_o P_1$	H_D
2-Phenylazo-pyridine	B	·00637	2·2929	3·2	0·60	0·85	183·2	156	57	99	2·2
	A		2·3048	5·1	0·96	1·21		222		165	2·8
3-Phenylazopyridine	B	·00562	2·2925	3·56	0·67	0·92	183·2	169	57	112	2·3
	A		2·2957	4·13	0·78	1·03		189		132	2·5
4-Phenylazopyridine	B	·00510	2·2970	4·80	0·90	1·15	183·2	211	57	154	2·73
	A		2·2951	4·43	0·83	1·08		198		141	2·61
4:4'-Azobis-pyridine	B	·00254	2·2790	2·56	0·48	0·73	184·2	135	55	80	2·0
	A		2·2775	1·97	0·37	0·62		114		59	1·7
4-Methyl-2-phenylazopyridine	B	·00306	2·2859	4·38	0·83	1·08	197·2	213	62	151	2·7
	A		2·2902	5·78	1·09	1·34		265		203	3·1
5-Bromo-2-phenylazopyridine	B	·00476	2·2859	2·82	0·53	0·78	262·1	204	65	139	2·6
	A		2·2879	3·24	0·61	0·86		226		161	2·8
3-5-Dibromo-2-phenylazopyridine	B	·00678	2·2788	0·93	0·17	0·42	341	143	73	70	1·8
	A		2·2800	1·11	0·21	0·46		157		84	2·0
2-o-Chlorophenyl-azopyridine	B	·00217	2·2778	2·44	0·46	0·71	217·7	155	62	93	2·1
	A		2·2818	4·29	0·81	1·06		231		169	2·9
3-o-Chlorophenyl-azopyridine	B	·00449	2·2868	3·18	0·60	0·85	217·7	185	62	123	2·4
	A		2·2896	3·81	0·72	0·97		212		150	2·7

B = BEFORE A = AFTER

Organic preparations

The preparation of azobis-pyridines by oxidising the corresponding amines with HOCl employed by Kirpal (46 and 35), was not unknown and had been used previously in the making of azobenzene homologues (84). The disadvantage was that with a reactive arylamine, substitution of chlorine in the nucleus occurred to some extent, (36) and (15). Where this was not probable, the method was extended with success, nitro- and bromo-2-amino-pyridines giving azo compounds in reasonable yield. 4:4'-Azobis-pyridine also made by this method may still have contained traces of chlorine in spite of its apparent homogeneity on columns of alumina and silica.

The alternative method of oxidising the amine with sulphuric acid and hydrogen peroxide, followed by reduction of the resulting nitropyridine to the azobis-pyridine was generally preferable. The pure nitropyridines are easily obtained, but insufficient heating of the reaction mixture during reduction can leave the azopyridine admixed with the corresponding azoxy compound. Even then in spite of repeated crystallisations from water or light petroleum, the highest temperature recorded for the melting of 3:3'-azobis-pyridine was 140°C (lit. 142°C). (But when cis-3:3'-azobis-pyridine reverted to trans on heat treatment, the m.p. was 142°C).

Phenylazopyridines/

Phenylazopyridines were synthesised by a reaction somewhat similar to both of those adopted by Faessinger and Brown (41). During the present research it was anticipated that the sodio derivative of 2-aminopyridine would react with nitroso compounds (the first method reported by Faessinger and Brown), but the much simpler condensation of amine and nitrosobenzene in contact with concentrated alkali was considered preferable and, as experience showed, gave very good yields.

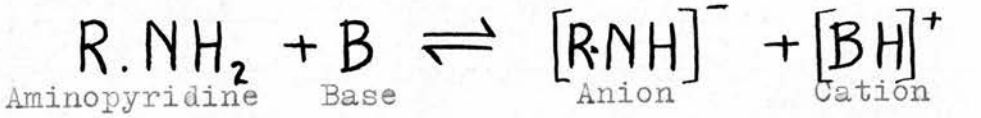
The second reported method entails the condensation of the disodium derivative of nitrobenzene with aminopyridines. This is comparable with the work of Martynoff (85) who made azocompounds with diamines and nitrobenzene in the presence of powdered NaOH.

From the results here obtained and from Martynoff's work, it appears that the actual sodium derivatives of the reactants were not required and that sodium hydroxide was a sufficient catalyst. No clear reason can at present be advanced for the failure of nitrosobenzene and amihopyridines to react in acid media. An approach to the problem can be made when it is remembered that the 2 and 4 aminopyridines are tautomeric with a pyridone-imide alternating with the normal amine structure (86), and it might be expected that the normal amine/

amine reactivity would be reduced, (c.f. also the difficult diazotisation (33)). It is notable, however, that benzaldehyde, resembling nitrosobenzene chemically,(87), condenses easily with 2-aminopyridine (46), and that 3-aminopyridine, a normal amine without a tautomeric form and easily diazotisable, couples with nitrosobenzene only under alkaline conditions. The tautomeric explanation must therefore be discarded.

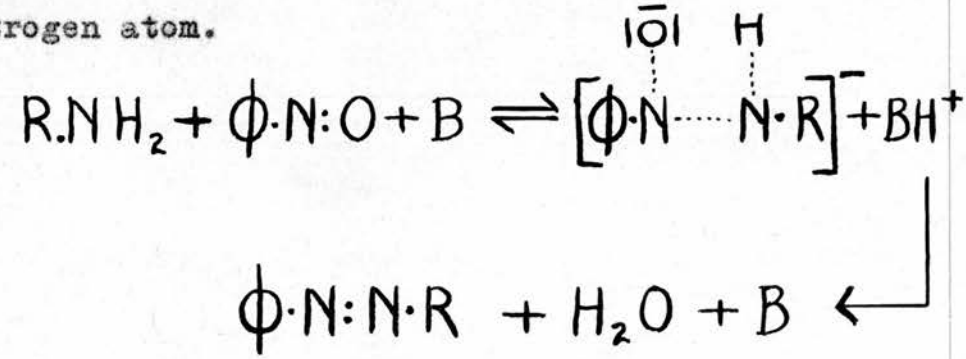
Compounds with sodium are formed by 2-aminopyridine and nitro and nitrosobenzaae (88) but as they are decomposed by water they have probably no place in the present condensations.

A tentative scheme may be put forward treating the reaction as an aldol or Perkin type. The rate-determining step may be

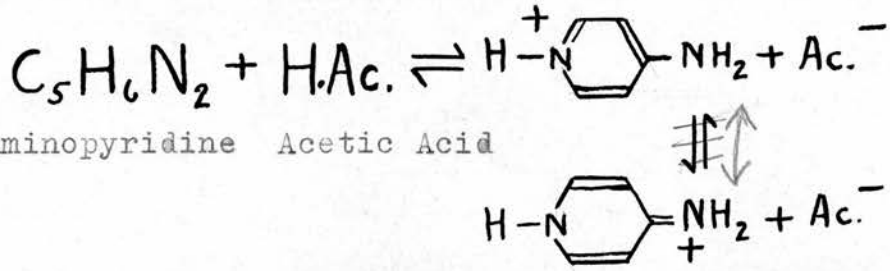


Also

The anion will then attack the positive nitrogen atom.



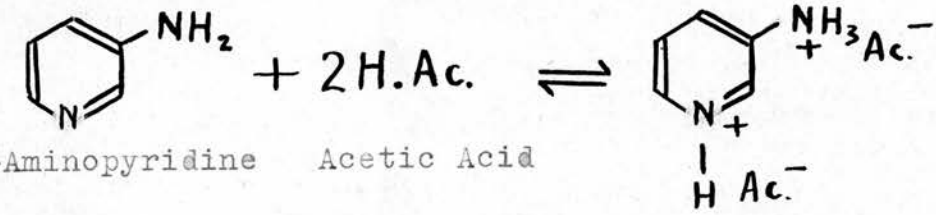
The non-reactivity in acid solution may then be accounted for as follows:



4-Aminopyridine Acetic Acid

The important resonating structure is seen to have a positively charged nitrogen which would not react with the nitroso group; 2-aminopyridine can similarly be accommodated.

The explanation does not include the 3-aminopyridine condensations unless we suppose that a positive charge can again be located at the amino group -



3-Aminopyridine Acetic Acid

A comparison may be made with the picolines which, having similar resonance structures to the aminopyridines are known to take part in aldol type condensations (89). Also, p-nitrosodimethylaniline condenses with 2 and 4-alkylpyridines to give azomethines (90) with a basic catalyst such as piperidine, which is generally in agreement with the scheme now proposed.

Polymorphism/

Polymorphism

Polymorphic behaviour in organic compounds is easily detected with Kofler's (or similar) apparatus, and by its use many unsuspected cases of polymorphism have been discovered e.g.veronal (91) and sterols (92). It is not surprising therefore that several examples have been encountered during the present studies.

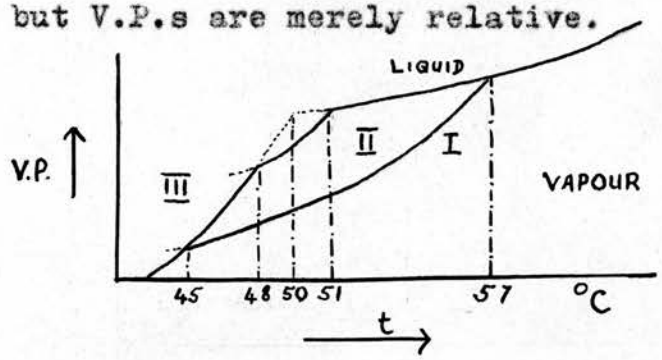
The first case observed occurred with azoxybenzene, which gave a monotropic modification melting at 29.5°C (P.V) as compared with 37.5°C for the stable form (P.VI). Azoxybenzene has been reported in two-component systems previously without suspicion of its polymorphic nature (93,94). When the molten substance is cooled quickly on a microscope slide the unstable spherulite form II appears, and on careful heating either melts at 29.5°C or is taken over by the higher-melting form I. Each form gives distinct eutectic temperatures with reference substances, and since no reversible transformation I⟶II can be observed, the relationship is monotropic. The azoxytoluenes similarly examined showed that O:O'-azoxytoluene was not polymorphic, that m:m'- was somewhat similar to azoxybenzene with a monotropic modification; while p:p'-azoxytoluene gave liquid crystals.

Janovsky/

Janovsky and Reiman (96) have reported a crystalline form of p:p'-azoxytoluene melting at 75°C compared to the normal type melting at 70°C. The liquid crystal form now noticed melted just below 70°C and no evidence of a form melting at 75°C was observed. With very careful cooling, liquid melt, normal crystals (I) and liquid crystals (II) could be obtained together; near 70°C I slowly and irreversibly took over II showing that this was a case of monotropy. Though unusual, monotropic liquid crystals are not unknown (97), and p:p'-azoxytoluene differs little from p:p'-azoxyanisole, which gives the best-known example of the enantiotropic type. It may reasonably be supposed that the azoxybenzene residue "lengthened" by other groups is capable of liquid crystal formation, the greater stabilisation being obtained when the "extension" is by groups which are polar in some degree, e.g. $-O-CH_3$ and $-O-\phi$, (98). Thus while the methoxy groups cause the appearance of stable enantiotropic liquid crystals in azoxyanisole the methyl group itself in azoxytoluene is enough to give monotropic liquid crystals. Discussing polymorphism and liquid crystalline formation, Vorländer (99) indicates that associative action with long molecules tends to result in liquid crystals and the present finding is in accordance/

accordance with this principle. It would be interesting to investigate the effect of longer paraffin chains in the p-positions in the azoxybenzene molecule.

O:O'-dichloroazoxybenzene, the other azoxy compound investigated, was shown to have a V.P./t. diagram as (XXXIV) where temperatures are quite accurate but V.P.s are merely relative.



XXXIV

(P. VII, VIII, IX) show the appearance when quick cooling of the melt crystallises I and II together. III quickly takes over II and less quickly I, these changes being reversible. Between 48 and 57°C, I supersedes II irreversibly. Other m.p.s and transformation points are shown.

It would thus appear that the aromatic azoxy compounds tend to assume polymorphic modifications, and in the case of p:p'- substituted materials this polymorphism may be of a liquid - crystalline nature. Also, increasing the polarity of substituents seems/

seems to increase the polymorphic tendency as is shown when the non-polymorphic O:O'-azoxytoluene is compared with the trimorphic O:O'-dichloroazoxybenzene.

Many of the azo compounds examined also showed polymorphic behaviour but this was generally unpredictable (99). However, it does seem that the assumption of new forms may be due to the easy "twisting" of the aromatic residues and their accommodation in different crystal systems. For example, 3-phenylazopyridine (I) has probably a flat molecule since it forms solid solutions with azobenzene, but (II) does not and hence this molecule is most likely not planar. Again, the polarity of substituents seems to affect the tendency towards polymorphism, e.g. mono- and dibromo-2-phenylazopyridine are polymorphic whereas 2-phenylazopyridine is not.

The evidence at hand is insufficient for further generalisations.

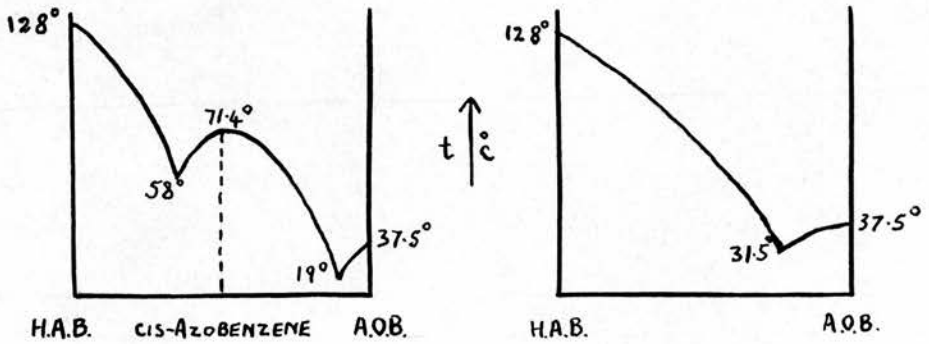
The system hydrazo-azoxybenzene and the melting behaviour of cis-azobenzene

Without direct experimental evidence, Hodgson made the claim that cis-azobenzene was a molecular compound of hydrazo and azoxybenzene,(26). Azoxybenzene does give a molecular compound with trinitrotoluene/

trinitrotoluene (100) and hydrazobenzene similarly with resorcinol (95), but it was considered unlikely that hydrazobenzene (H.A.B.) and azoxybenzene (A.O.B.) would condense together as a molecular compound without elimination of water. Heating with alcoholic potash (101) is reported as being necessary for the reaction A.O.B. + H.A.B. azobenzene + water.

Nevertheless, Le Fevre (29) examined the system H.A.B. + A.O.B., finding a simple eutectic below 20°C. This eutectic has now been established on a contact-prep. at 31.5°C, and the eutectic region while in the liquid state could not be induced to crystallise as a result of seeding with either cis- or trans-azobenzene at temperatures between 25 and 60°C. This appeared to show the absence of any form of azobenzene.

Both the melting point diagrams (XXXV) and (XXXVI) have been determined by contact-preps. and according to H. the H.A.B. - A.O.B. system should be (XXXV) whereas it was in fact found to be (XXXVI).



XXXV XXXVI

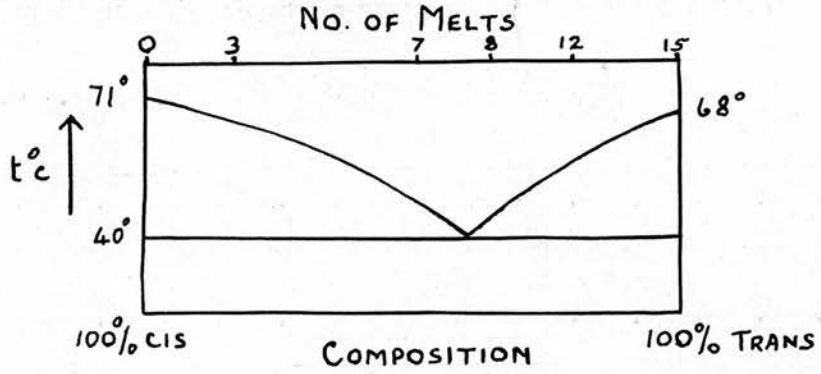
The low eutectic temperature, 19°C, between cis-azobenzene and A.O.B. is a further indication that there is no azobenzene present in the normal system H.A.B. + A.O.B. where the eutectic is as high as 31.5°C. K. Hyrnakowski (95) reports simply a mechanical mixture between A.O.B. and H.A.B.

X - ray powder photographs of H.A.B., A.O.B. and mixtures of the two (XXV 3,4,5,6) recrystallised together at room temperature and at 80°C showed again that simple mechanical mixtures existed. Photographs of these mixtures showed no resemblance to those of cis and trans-azobenzene (XXV,1,2). Examination of cooling curves of the system showed similarly the absence of compound formation, and, in fact, considering that cis-azobenzene is destroyed by heating (see below) it is unlikely to be formed by melting together two "components".

If H.'s interpretation is correct, hydrazobenzene and azoxybenzene would have to be formed in dry solvents during irradiation and combine to form the cis compound. Le Fevre (29) has further shown this to be unlikely since azoxybenzene under the influence of ultra-violet light is transformed to o-hydroxyazobenzene (102). On the other hand, water might be supposed to combine with trans-azobenzene directly to give "cis" but this would be equally unlikely in solvents dried with sodium wire.

The/

The melting behaviour of cis-azobenzene confirms the previous observation, (12) that it is transformed into trans on heating above the m.p. This transformation has been followed from 100% cis to 100% trans by successively heating and cooling. The melting-point diagram for the cis-trans system has been established (XXXVII) with a eutectic at 40°C.



Melt No. 7 was kept for 5 minutes at 70°C.

XXXVII

This diagram is the same as would be obtained if for each melting experiment a synthetic mixture of cis and trans were taken instead of as here, the product of transformation. Heating and cooling accelerates the change to trans which is seen to be nearing completion when the more rounded cis habit no longer appears at equilibrium (P.XXI) and the characteristic spear-shaped trans is seen (P.XXII). This is unlike anything in the system H.A.B. and A.O.B.

Since during the melting - solidifying procedure (a) no water is formed, and (b) the only end product is undoubtedly azobenzene, it seems impossible/

impossible that the starting material could be any other than a geometrical isomer. Considering the previous evidence and that now brought forward it is thought unlikely that Hodgson's statement is correct and henceforth it is assumed that cis azo compounds are true geometrical modifications of trans isomers.

Mixed-crystal formations of azo-compounds

It is well-known that substances of similar constitution and spacial configuration form solid solutions. Starting from the familiar Type I (Roozeboom) system, viz. trans-azobenzene-stilbene, Kofler and Brandstätter (103), have investigated binary mixtures of azobenzene, stilbene, dibenzyl and benzalaniline. When solid solutions expected from structural considerations did not occur, unstable polymorphic modifications of components were found to give the anticipated types of diagram. Thus the stable, non-planar form of dibenzyl did not form solid solutions with stilbene, azobenzene, or tolane whose molecules are flat, (104) but an unstable modification had this property and hence is considered to be flat also. A similar relationship was found with benzalaniline.

Thus it appeared that in these compounds consisting of two benzene nuclei joined by such groups as - N = N - and - CH = CH -, an indication of similarity/

similarity of configuration could be inferred from the presence among them of solid solutions. The change of the central group had little effect on the type of system found.

Now Bergman, Engel and Sandor (105) have stated that neither azobenzene not stilbene give solid solutions with iso-stilbene. Providing that pairs of compounds such as cis-azobenzene and isostilbene gave with each other solid solutions, an easy method of identifying cis compounds might then be at hand. To be useful the central group, cis or trans, would have to dominate the binary system.

Two of the most stable cis compounds so far known, cis- p-iodoazobenzene and cis-m-nitroazobenzene (15) were accordingly made and though they showed no indication of solid solution formation with several trans azo compounds, no more did such a system occur between the two cis isomers. The important factors in two-component systems of this nature thus seemed to be the substituents in the aromatic nuclei as well as the configuration, cis or trans, of the central group. Further investigations with cis and trans-azopyridines showed that there was no relationship between configuration of the central azo groups and the phase-diagram given by two substances.

(Stable/

(Stable reference substances might have been the α and β, 1:2-1':2'-tetraphenyl-3:3'-azobis-indoles of Huang-Hsinmin and Mann (39), which, however, melt at too high temperatures to be useful and α hardens to a glass; and further, from absorption spectra (XXVII) it is not clear that these two substances are true cis and trans isomers.)

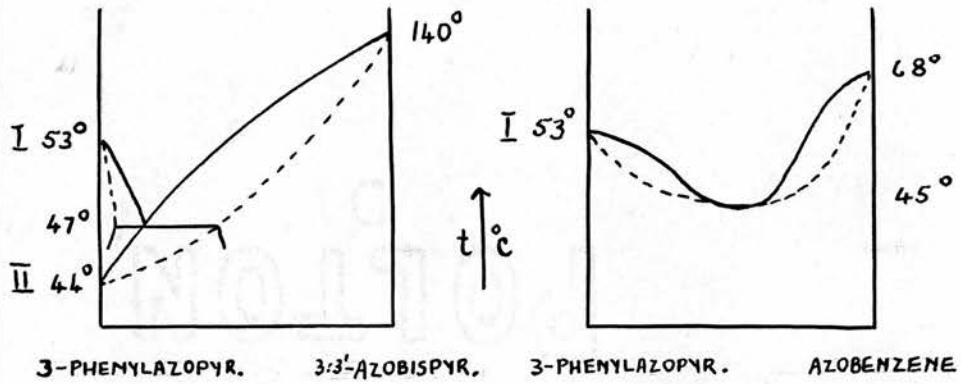
In fact even with similarity of configuration of the azo groups, great resemblance of the aromatic residues was necessary before solid solutions would occur.

Some purely trans compounds are worthy of further mention. Thus it appeared that 2-phenylazo-pyridine formed type I solid solutions with 2:2'-azobis-pyridine but not with azobenzene. This could be due to a configuration of azobenzene different to that of either pyridine compound, but is more likely to be attributable to the dissimilarities in the aromatic nuclei.

An interesting case was that of 3-phenylazo-pyridine, the unstable form (II) giving solid solutions, Type I with 3:3'-azobis-pyridine, and the unstable form (I) having a Roozeboom Type III system with azobenzene (XXXVIII).

Unstable 3-phenylazopyridine (II) and 3:3'-azobis pyridine must therefore have very similar configurations which differ somewhat from both 3-phenylazopyridine (I)/

(I) and azobenzene. The latter pair resemble one another less closely than the former pair, and since azobenzene is itself planar, so also may be 3-phenylazopyridine (I).



XXXVIII

Surprisingly, 4:4'-azobis-pyridine gave no simple solid solutions with either 4-phenylazopyridine or azobenzene and the latter two components together appeared to have a simple eutectic; also no solid solution could be observed with 4:4'-dimethyl-2:2'-azobis-pyridine and 4-methyl-2-phenylazopyridine in any of its forms.

The conclusion we can arrive at is that though solid solution is not to be expected with cis-A and trans-B, it is no more necessary for cis-A + cis-B or indeed trans-A + trans-B to give this type of system. No solid solution system was found with cis components and when it did occur with trans materials, great similarity of dimensions and constitution was obviously/

obviously necessary, the methyl groups in the case of 4-methyl-2-phenylazopyridine + 4:4'-dimethyl-2:2'-azobis-pyridine being enough to disturb the type I system existing with the unsubstituted nuclei. But to apply the principles of Pascal and Normand (106) it would appear that 4-methyl-2-phenylazopyridine would form solid solutions with 2-p-toluenazopyridine and 4:4'-dimethyl-2:2'-azobis-pyridine with 4-methyl-2-p-toluenazopyridine.

Cis-trans Isomerism in the Azopyridine Series

The first claim to have isolated an isomeric azopyridine was made by Kirpal and Bohm (35) who obtained what they thought was a second form of 2:2'-azobis-pyridine; but this they later showed to be simply an impure form of the familiar substance. The difficulty of separation and purification has now been shown to be due to solid solution formation between the azopyridine and the impurity 5-chloro-2:2'-azobis-pyridine. The presence of small quantities of thd chloro compound during crystallisation changed the habit from deep red needles to the flaky orange plates of Kirpal's lower-melting "isomer". His later work (36) was confirmed when a simple method of separating the chloro compound was found to be by partition chromatography, and X - ray powder photographs (XXIII) showed the essential identity of the/

the flakes (m.p. 83-83°C) and the needles (m.p. 86°C). On a microscope slide the pure compound recrystallised as needles while the impure material had a spherulitic structure; eutectics and molecular compounds with suitable materials further confirmed Kirpal's ultimate conclusion.

From previous work in the azobenzene series (12) and from theoretical considerations of cis-trans isomerism (107) it seemed that if the azopyridines existed as geometric isomers, the change trans to cis would be made by the action of light. This has now been done and separations of 2:2'- and 3:3'-azobis-pyridines as typical cis isomers has been effected chromatographically. When such isomerism occurs, cis compounds are frequently more hydrophilic than trans (15,108), but this is not necessarily so and separations depend not only on the compounds but also on the adsorbent and solvent used (109).

Since the azopyridines were too strongly adsorbed by alumina, recourse was again had to silica gel and partition chromatograms. Separation on such columns showed that trans-2:2'- and cis-3:3'-azobis-pyridines were the more hydrophilic isomers. 3:3'- was thus "normal", but owing possibly to the great affinity of trans 2:2'- for water (36), reversal of the expected order occurred here/

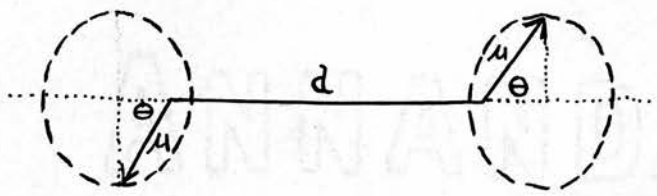
here.

The ultra-violet absorption spectra of the 2:2'-azobis-pyridines (XXVI) resembled those of analogues in the azobenzene series (XXV), (17); and the hypsochromic effect following the change trans to cis, seemed to indicate decrease of molecular planarity, (110). This agreed also with the x-ray findings of Robertson on the azobenzenes, (64, 21). A scale drawing (XXXIX) of the probable cis molecule based on the most recent dimensions of the pyridine nucleus, (111), and other bond - lengths from cis-azobenzene (21), with the addition of Stuart's "Wirkungsradien", (112) shows that planarity would be impossible in a molecule of this type.

The distinct nature of the new cis isomers has been shown with x-ray powder photographs (XXIII) and the possibility of polymorphism was eliminated when it was found that eutectics for each pair existed, which were lower that the m.p. of either.

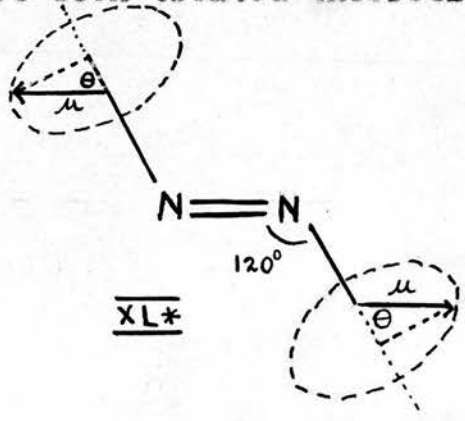
The results of dipole-moment determinations (Tables IV and V) were also in agreement with those of parallel cases. Errera (113) showed that cis-dichloroethylene had a dipole moment of 1·89D while that of trans was zero. Similarly Hartley and Le Fevre (18) found that cis-azobenzene had a moment of 3D, that of the trans isomer again being zero. A system comparable to the azopyridines viz. the ethyl/

ethyl esters of maleic and fumaric acids was dealt with by Briner, Perrottet and Susz (114), who found that ethyl maleate and fumarate had dipoles of 2·51 and 2·23D respectively. In compounds such as these and the azopyridines, by rotation of the polar groups, a resultant dipole will be found for trans molecules as well as cis. The simple case of substances of the type of ethylene dichloride can be treated mathematically (115), and the resultant dipole assuming free rotation (XL) is given by $\bar{\mu}$ observed = $\sqrt{2}\,\mu \sin\theta$ where μ is the value of each doublet contributing, and θ is the angle to the axis along which they act. When d, the



XL

distance apart becomes great, the agreement with theoretical values is satisfactory (67, p.92). In the case now considered, the doublets do not rotate round the same axis (XL*) and the problem does not yet appear to have been treated theoretically.



XL*

Furthermore, though the dipole moment of the pyridine nucleus seems generally to be accepted as 2·2D the direction of the dipole is uncertain, (116, 117 and 118). Again, precise structures of the azopyridine molecules are unknown.

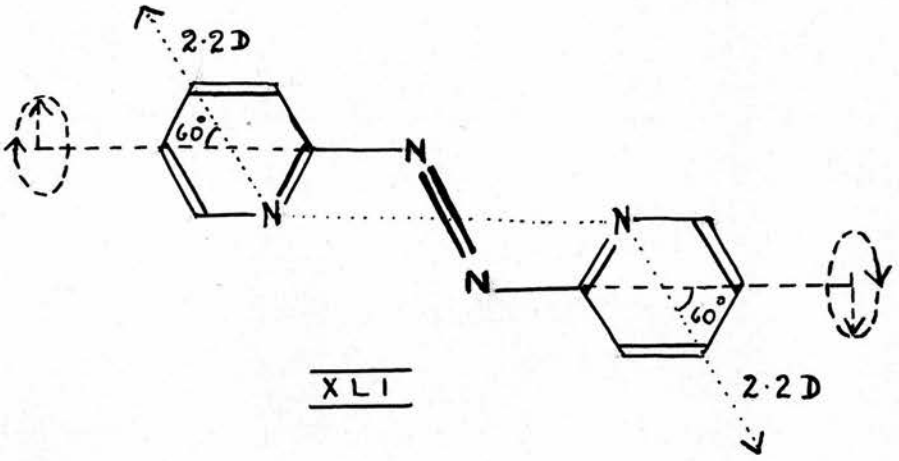
With these considerations in mind it is impossible accurately to predict values of the dipoles of the azobis-pyridines but the magnitude in the 2- and 3- series should still be less for the trans than for the cis isomers. The values observed were (Table VI from Table IV).

Table VI

Azobis-pyridine	Cis	Trans
2:2'-	4 D	1·8D
3:3'-	2·8D	2·5D

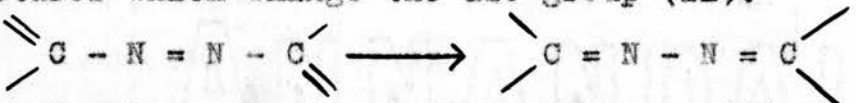
It is assumed henceforth that in pyridine the dipole, 2·2D, acts from the γ carbon atom towards the ring nitrogen, the latter being negative (117). If also, the formula of Williams (loc. cit.) is assumed to give an indication of magnitude of dipole moment to be expected, then $\bar{\mu}$, the resultant dipole moment is 2·7D for 2:2'-azobis-pyridine (XLI) $\theta = 60^{\circ}$.

That the observed moment was considerably less/



XLI

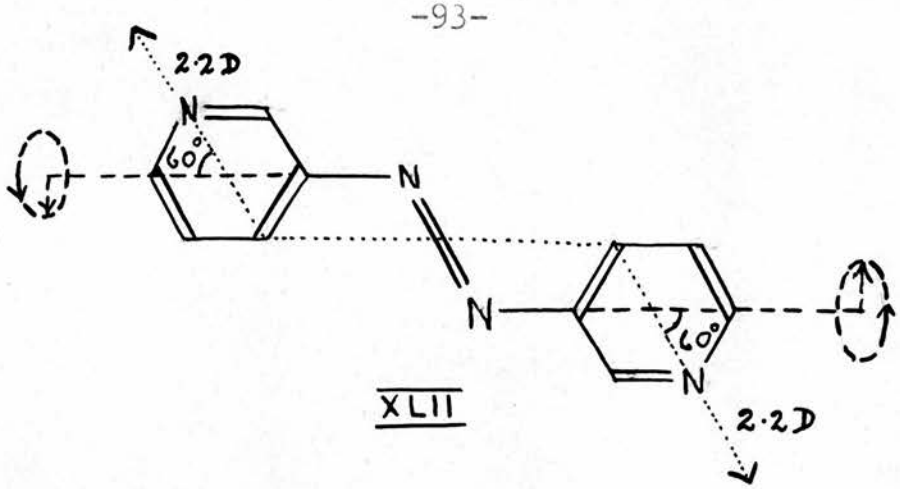
less than this is undoubtedly due to restricted rotation of the pyridine nuclei (67, p. 92). While dipolar interference will be contributary a more probable cause will be the effect of resonating structures which change the azo group (21).



and obviously prevent rotation of the pyridine nuclei alone. Pauling (119) comments on the considerable contribution to the resonance energy of trans azobenzene and stilbene from such sources and it is therefore not unlikely that resonance of a similar nature occurs here with the attendant hindrance of rotation.

Again assuming $\theta = 60^{\circ}$ in the 3:3'-azobis-pyridine (XLII) molecule, the calculated value of μ is 2·7D and the experimental value is 2·5D.

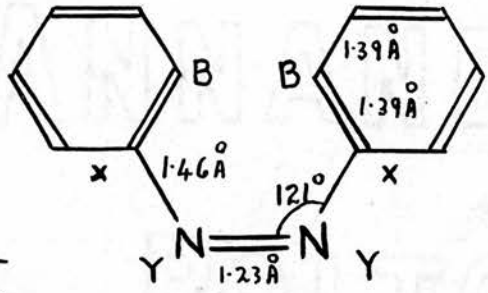
It then appears that rotation is not so restricted and/or the resonance energy is less than in/



XLII

in the previous example. Its relative insolubility is water might also be explained by the decrease in resonance.

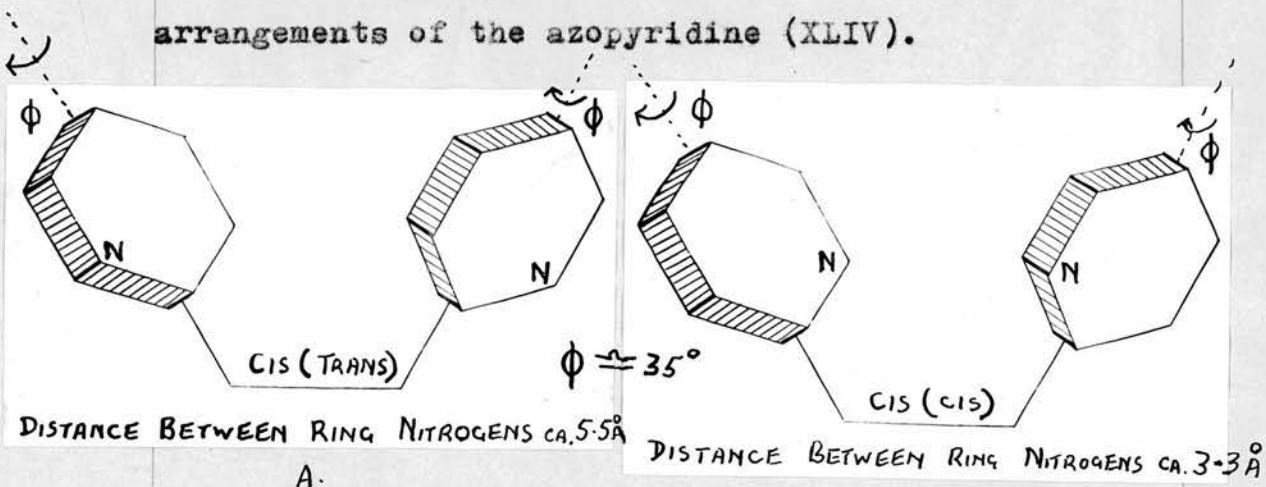
The cis molecules would appear to be much more rigid.



XLIII

(XLIII) In cis-azobenzene, the carbon atoms B, approach to 3·3Å which is below the van der Waals distance for free rotation (21). This means that though bonds XY must have single-bond character for the existence of the cis molecule, yet rotation of the aromatic nuclei is unlikely. In cis-2:2'-azobis-pyridine it is probable that the ring nitrogens are trans to one another (40) and, considering cis-azobenzene/

azobenzene it is possible to visualise two such arrangements of the azopyridine (XLIV).



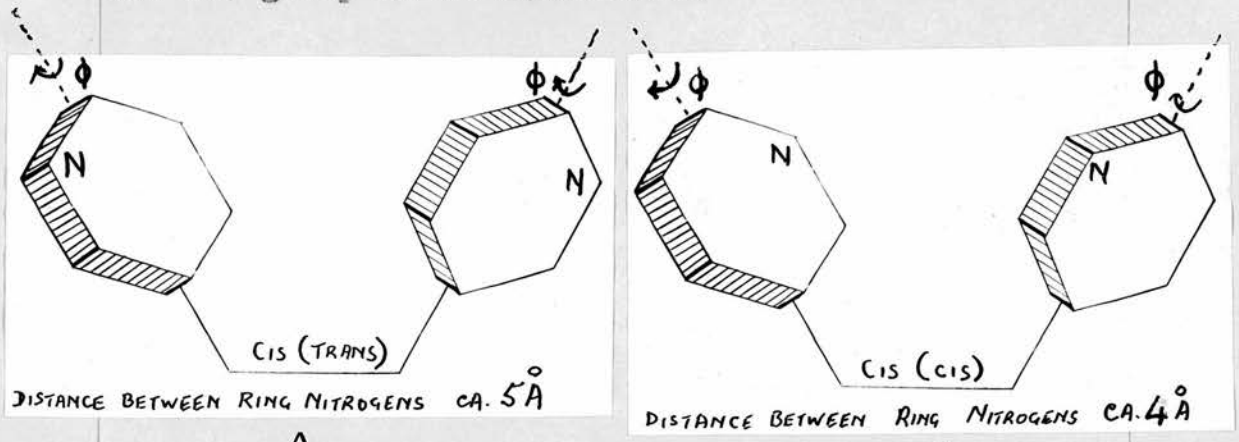
XLIV

(Optical isomerism appears possible).

Mutual repulsion by ring nitrogens would seem to favour A. But the observed dipole is 4D which, allowing 3D for the cis-azo dipole, leaves only 0·5D to be contributed by each pyridine residue. Though dipole interaction must reduce the observed resultant yet A would probably cause a larger value than is found; and B then appears the more likely. Pauling gives the effective Van der Waals radius of a nitrogen atom as 1·5Å and half the thickness of an aromatic molecule as 1·85Å (119, p. 189) which means that from steric considerations alone the ring atoms ortho to the azo group can approach closer when they are nitrogens instead of carbon - hydrogen groups. If this were the case, "screening" of the ring nitrogens might explain the surprising insolubility/

insolubility in water of cis-2:2'-azobis-pyridine and the apparent absence of a molecular compound with phenylacetic acid.

The observed moment of cis-3:3'-azobis-pyridine is 2·8D and this again is in agreement with the known facts. It is more soluble in water than either 3:3'-trans or 2:2'-cis so the ring nitrogens may be less "protected" than in the latter. On the other hand increase of solubility may be due to the cis azo group as in azobenzene.



XLV

To obtain the very small reduction to 2·8D from the azobenzene value of 3D, form A (XLV) has to be assumed with considerable polar neutralisation between the ring dipoles and/or twisting of the rings through quite a large angle ϕ. Any position of B would give too great a reduction from 3D to be probable. It is clear that while generally indication of cis-trans isomerism in the 2:2'- and 3:3'-azobis-pyridine, dipole moment evaluations cannot/

cannot give exact predictions of the fine-structure of the molecules.

Single solutions of the following were examined and the approximate dipole values are recorded here before and after irradiation with u.v. light. Table VII.

Table VII

Substance	Apparent Dipole in D	
	Before Irradiation	After Irradiation
2-Phenylazopyridine	2·2	2·8
3-Phenylazopyridine	2·3	2·5
4-Phenylazopyridine	2·7	2·6
4:4'-Azobis-pyridine	2·0	1·7
4-Methyl-2:2'-azobis-pyridine	2·7	3·1
3:5-Dibromo-2-phenyl-azopyridine	1·8	2·0
5-Bromo-2-phenylazo-pyridine	2·6	2·8
2-o-Chlorophenyl-azopyridine	2·1	2·9
3-o-Chlorophenyl-azopyridine	2·4	2·7

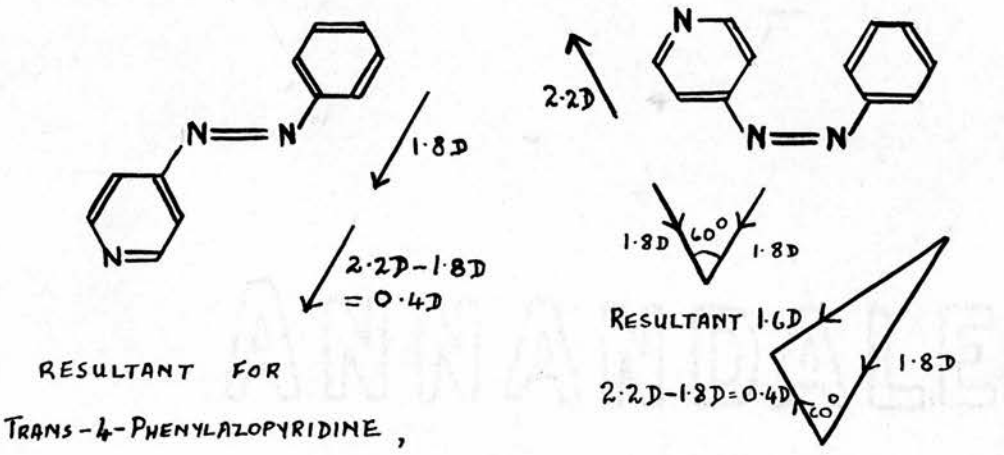
(From Table V.)

All substances examined showed μ, and apparent change in μ, of the magnitude to be expected if cis and trans isomers exist.

2 and 3-phenylazopyridines with moments of

2·2/

2·2 and 2·3D respectively before irradiation had apparently trans configurations with the dipole due largely to the pyridine nucleus. This is also no doubt the case for 4-phenylazopyridine, in which a slight decrease of moment was observed on irradiation. Assuming that the moment 3D, of cis-azobenzene, is made up of two components of approximately 1·8D acting at 60° to each other, probable values for dipoles of phenylazopyridines can be found (XLVI).



XLVI

The moments calculated for the 4-compound from the diagrams above (XLVI) were 2·2D for the trans and 1·6D for the cis. Since a decrease in dipole moment was actually observed on irradiation this could be taken as indicative of partial transformation to the cis isomer.

The/

The same arguments apply to the 4:4'-azobis-pyridine where the calculated value of the cis dipole was 0·7D, much less than the 2D observed for trans. That the latter has a dipole is probably due to splaying and rotation of the pyridine rings, while the apparent change of dipole moment on irradiation was in the direction to be expected from the appearance of a cis form. (Absorptiometer experiments also showed slight decreases in the blue-green absorption when 4-azopyridines were irradiated).

Leis and Curran (117) give μ for γ-picoline as 2·6D, which when μ of pyridine is 2·2D means that the γ methyl group contributes 0·4D. 4-Methyl-2-phenylazopyridine had an observed dipole of 2·7D, 0·5 more than 2-phenylazopyridine showing quite good agreement with the difference to be expected from the work referred to.

Thus, while it is emphasised that only single solutions were examined, the evidence obtained was sufficient to demonstrate the general principle that the azopyridines listed in table (VII) are normally trans and by the action of light can be partially transformed into cis.

CONCLUSION

A number of azopyridines have been synthesised and classified by their appearance and behaviour on Kofler's micro-melting point apparatus.

Hodgson's refutation of the occurrence of cis azo compounds has been critically examined and work carried out on azo compounds in the pyridine and benzene series showed that his theory is erroneous.

A simple meter was constructed for the measurement of dipole moments and values determined for members of the azopyridine series were in accordance with the theory that cis and trans isomers exist. Two new cis compounds were isolated.

The widespread occurremce of polymorphism among organic compounds was emphasised when it was found that about 50% of those substances examined crystallised in two or more solid forms.

REFERENCES

1. Hartley, G.S. Nature, 1937/140/281.
2. Maitland, P. Ann. Reps., 1939/241.
3. Mills, W.H. J., 1931/537.
4. Pauling, L. and Brockway, L.O. J.A.C.S., 1937/59/13.
5. Hantzsch and Reddelien. "Die Diazoverbindungen", Springer, 1921, p.35.
6. Müller, E. Annalen, 1932/493/166.
7. Warburg. Ber. Berl. Akad., 1919/960.
8. Smakula, A. Z. phys. Chem., 1934/B25/90 (B25-26).
9. Brady, O.L. and McHugh, G.P. J., 1924/125/547.
10. Bergmann, E., Engler, Leo and Sandor, R. Ber., 1930/B63/2572.
11. Robertson, J.M., Prasad, M. and Woodward, G. Proc. Roy. Soc., 1936A/154/187.
12. Hartley, G.S. J., 1938/633
13. Zechmeister. Naturwiss, 1938/26/495.
14. Cook, A.H. J., 1938/876.
15. Cook, A.H. and Jones, D.G. J., 1939/1309.
16. Burawoy. J., 1937/1869.
17. Cook, A.H., Jones, D.G. and Polya, J.B. J., 1939/1315.
18. Fevre, R.J.W.Le and Hartley, G.S. J. 1939/531.
19. Gehrckens, K. and Müller, E. Annalen, 1933/500/296.
20. Robertson, J.M. J., 1939/232.
21. Robertson, J.M. and Hampson, G.C. J., 1941/409.
22. Cook, A.H. and Jones, D.G. J., 1941/184.
23. Calderbank, K.E. and Le Fevre, R.J.W. J., 1948/1949.
24. Von Anwers, K. Ber., 1938/B71/611.

25./

25. Winkel, A. and Siebert, H. Ber., 1941/B74/670.

26. Hodgson, H. J. 1948/1102.

27. Hodgson, H.H. Chem. and Ind., 1947/774, ibid. 1948/270, 428, 588 and J. Proc. R.I.C., 1947/6/428.

28. (a) Le Fevre, R.J.W. Chem. and Ind., 1948/26/158 - (b) Calderbank, K.E., Le Fevre, R.J.W. and Northcott, J.; 543 - (c) Le Fevre, R.J.W. and Northcott, J.; 732 - (d) Le Fevre, R.J.W., (e) Northcott, J. and Wilson, I.R.; 782 - Le Fevre, R.J.W. and Northcott, J. and J. 1949/1595 - (f) Le Fevre, R.J.W. and Souter.P.

29. Waters, W.A. Chem. and Ind., 1948/26/301.

30. "Mikro-Methoden zur Kennzeichnung organischer Stoffe und Stoffgemische". A. & L. Kofler, Innsbruck, Universitatsverlag, Wagner, 1948.

31. Tschitschibabin, A. and Seide, O. Chem. Zentr., 1915/I/1065.

32. Tschitschibabin, A. and Seide, O. Chem. Zentr., 1923/III/1022.

33. Koenigs, E. Angew. Chem., 1937/50/911.

34. Chichibabin, A.E. and Ossetrowa, E.D. J.A.C.S., 1934/56/1711.

35. Kirpal, A. and Bohm, W. Ber., 1932/B65/680.

36. Kirpal, A. Ber., 1934/B67/70.

37. Bystritskaya, W.G. and Kirsanov, A.V. C.A., 1941/35/4023., from J. Gen. Chem. U.S.S.R., 1940/10/1101.

38. Wiley, R.H. and Hartman, J.L. J.A.C.S., 1951/73/494.

39. Huang Hsinmin and Mann, F.G. J., 1949/2903.

40. Le Fevre, R.J.W. J., 1951/1814.

41. Faessinger, R.W. and Brown, E. J.A.C.S. 1951/73/4606.

42. McCrone, W.C. and Anal. Chem., 1949/21/436.

43. Zechmeister, L. and Rom, P. Annalen, 1928/468/117.

44./

44. Cohen "Practical Organic Chemistry", p.162, (MacMillan).

45. Bamberger, E. and Hubner, R. Ber., 1903/36/3818.

46. Kirpal, A. and Reiter, E. Ber., 1927/B60/664.

47. Martin and Synge, R.M. Biochem. J., 1943/37/79.

48. Tschitschibabin, A.E. Chem. Zentr., 1923/III/1021.

49. Caldwell, W.T. and Kornfeld, E.C. J.A.C.S., 1942/64/1696.

50. Organic Syntheses - Vol. 30, p.3.

51. Friedl, F. Monat, 1913/34/759.

52. Kirpal, A. and Reiter, E. Ber., 1925/B58/699.

53. Schofield, K. Quart. Rev., 1950/No. 4/Vol.4/p.382; and Hertog, H.J. Den, Jr. and Overhoff, J. Rec. Trav. Chim., 1930/49/552.

54. Hertog, H.J. Den and Overhoff, J. Rec. Trav. Chim., 1950/69/468.

55. Organic Syntheses - Vol. 25, p.86.

56. Ingold, C.K. J., 1925/127/516.

57. Ruggli, P. and Bartusch, G. Helv. Chim. Acta, 1944/27/1371.

58. Organic Syntheses - Vol. 25, p.80.

59. Lutz, R.E. and Lytton, M.R. J. Org. Chem., 1938/2/72.

60. Koenigs, E., Freigang, W., Lobmayer, G. and Zscharn, A. Ber., 1926/59/321

61. De Milt, C. and Van Zandt, G. J.A.C.S., 1936/58/2044.

62. Nystrom, R.F. and Brown, W.G. J.A.C.S., 1948/70/3738.

63. Bunn "Chemical Chrystallography", p.114, (Clarendon Press).

64. De Lanze, J.J. and Robertson, J.M. Proc. Roy. Soc., 1939/A171/398.

65./

65. Daniels, Mathews and Williams "Experimental Physical Chemistry", p. 151, (McGraw-Hill).

66. Philip, J.C. J., 1903/83/814.

67. Le Fevre "Dipole Moments", (Methuen 1948).

68. Gent, W. Trans. Far. Soc., 1949/45/758.

69. Fischer, R.B. Anal. Chem., 1947/19/835.

70. Thomas "Theory of Valve Oscillators", (Chapman and Hall 1939).

71. Clifford. Electronic Eng., 1945/560.

72. Hedestrand, G. Z. physik. Chem.,B1929/2/428.

73. Le Fevre, R.J.W. Trans. Far. Soc., 1950/46/1.

74. Le Fevre, R.J.W. and Russell, P. J., 1936/491.

75. Le Fevre, C.J. and R.J.W. J., 1936/1136.

76. Jenkins, H.O. J., 1934/482.

77. Thomson, F.W. and Ubbelohde, A.R. Trans. Far. Soc., 1950/46/353.

78. Le Fevre and Vine. J., 1937/1805.

79. Guggenheim, E.A. Trans. Far. Soc., 1949/45/714 and Smith, J. ibid. 1950/46/394, and Everard, K.B., Hill, R.A.W., and Sutton, L.E. ibid. 1950/46/417.

80. Guggenheim, E.A. Trans. Far. Soc., 1951/47/573.

81. Sugden, S. Trans. Far. Soc., 1934/30/720.

82. Anderson, J.D.C., Le Fevre, R.J.W. and Wilson, I.R. J. 1949/2082.

83. Lipkin, W.R., Davison, J.A., Harvey, W.T. and Kurtz, S.S., Jr. Anal. Chem., 1944/16/55.

84. Meigen, W. and Normann, W. Ber., 1900/33/2716.

85. Martynoff, L. Cont. Rend., 1948/227/1371.

86. Tschitschibabin, A.E. Ber., 1924/B57/1168 and 1927/B60/1607; Koenigs, E., Mields, W. and Gurlt, H. Ber., 1924/B57/1179.

87./

87. Hendricks, S.B. and Hilbert, G.E. J.A.C.S., 1931/53/4280.

88. Lukaschewitsch, W.O. Annalen, 1935-36/521-2/198.

89. Elderfield "Heterocyclic Compounds", Vol. I, p.445, (Wiley).

90. Kaufmann, A. Ger. Pat. 243, 078, Jan. 4, 1911 (C.A. 1912/6/2291); Kaufmann, A. and Vallette, L. Ber., 1912/45/1736 and 1913/46/49.

91. Kofler, A. Mik., 1948/33/8.

92. Gilpin, V. Anal. Chem., 1951/23/365.

93. Hartley, H. and Stuart, J.M. J., 1914/105/309.

94. Fry, H.S. and Cameron, J.L. J.A.C.S., 1927/49/864.

95. Hyrnakowski, K. Atti. 8 X congr. intern. chim. 1939/3/197.

96. Janovsky, J.V. and Reimann, K. Ber., 1889/22/40, and 1172.

97. Vorlander, D. Trans. Far. Soc., 1933/29/901.

98. Discussion on Liquid Crystals, Trans. Far. Soc., 1933/29/881-1085, particulalry Bernal, p.1034.

99. Vorlander, D. Ber., 1937/B70/1202.

100. Giua Michele e Guastalla Guido Gazz. Chim. ital., 1925/55/646 (C.A. 20/1062).

101. Freundler, P. Bull. Soc. Chim., 1904/31/459.

102. Knipscheer, H.M. Rec. Trav. Chim., 1903/22/1.

103. Kofler, A and Brandstatter, M. Z. physic. Chem., 1942/A190/34 and Brandstatter, M. Z. physic. Chem., 1943/192/76.

104. Robertson, J.M. and Woodward, I. Proc. Roy. Soc., 1937A/162/568 and 1938A/164/436.

105. Brunetti, C. Proc. R.I.E., 1939

106. Pascal, P. and Normand, L. Bull. Soc. Chem. France, 1913/13/878.

107. Olson, A.R. and Hudson, F.L. J.A.C.S., 1933/55/1410.

108./

108. Wyman, G.M. and Brodie, W.R. J.A.C.S., 1951/73/1487.

109. Freundlich, H. and Heller, W. J.A.C.S., 1939/61/2228.

110. Blumberger, J.S.P. Rec. Trav. Chim., 1944/63/127.

111. Allen, P.W. and Sutton, L.E. Acta. Cryst., 1950/3/46.

112. Stuart, Z. phys. Chem., 1935/B27/350.

113. Errera. J. Phys. Radium, 1925/6/390.

114. Briner, E., Perrottet, E., Susz, S. and Paillard, H. Helv. Chim. Acta., 1937/20/762.

115. Williams, J.W. Z. phys. Chem., 1928/138/75.

116. Rau, M.A.G. and Narayanaswamy, R. Z. phys. Chem., 1934/B26/23.

117. Leis, D.G. and Curran, B.C. J.A.C.S., 1945/67/79.

118. Orgel, L.E., Cottrell, T.L., Dick, W. and Sutton, L.E. Trans. Far. Soc., 1951/47/113.

119. Pauling, L. "The Nature of the Chemical Bond".

ACKNOWLEDGEMENTS

I am deeply indebted to Dr. Neil Campbell and Dr. Duncan Taylor for their enthusiastic interest and friendly encouragement during the period of research. Without their helpful suggestions and discussions the work would indeed have been impossible.

For advice on electrical apparatus I thank Prof. H.D. Springall and Mr. F.P. Henderson, B.Sc. Mr. A. Hodkin kindly prepared some of the azobenzene derivatives.

Thanks are also due to the Department of Scientific and Industrial Research for a Maintenance Grant during the tenure of which the work was carried out.

6. 91:

§46: X-ray powder photographs : DAT
§81
49 Cooling curves DAT
supplements the hot stage work
57 Absorption spectra DAT Include Derivatives.
52 Density measurements. DAT.

p. 80. Henderson's interpretation of Hodgson's work is not quite correct. Are the eutectics for trans-aqueous and hydrocarbon-aqueous & aqueous known?

Yes p13, 16

No p. 82. Include photographs?